Gerard A.J.M. Jagers op Akkerhuis
Editor

Evolution and Transitions in Complexity

The Science of Hierarchical Organization in Nature

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ISBN 978-3-319-43801-6 ISBN 978-3-319-43802-3 (eBook)
DOI 10.1007/978-3-319-43802-3

Library of Congress Control Number: 2016954246

Printed on acid-free paper

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

Preface

This book offers an integration of the results of a scientific quest that started in 1994. The quest's goal was to identify levels of complexity in the organisation of nature. For the identification of such levels a scientific tool was developed, a "complexity ladder" that was named the Operator Hierarchy. This ladder adds many new insights to the classical ladder of nature, known as the scala naturae, which offered an allegorical ranking of kinds of entities according to "increasing perfection." The scala naturae started with minerals and extended to plants, animals, humans, angels, and god.

There are many reasons why few people consider the classical ranking a scientific approach, for example because it lacks mechanisms and includes non-material entities (e.g. angels). Because of such incongruences, the scala naturae has contemptuously been classified as an archaic approach that should be abolished, like scientists have abolished the idea that the sun orbits the earth. However, if one categorically rejects all ideas about ladders, one risks throwing the baby of hierarchical thinking out with the bathwater of allegorical thinking.

A new, mechanistic scala naturae

This book explores the hierarchy that emerges when several existing objects integrate to form a single new object, after which the process repeats with the newly formed objects, etc. In this book it will be explained how, amidst many possibilities, the Operator Theory singles out one specific ranking of kinds of objects and how this special ranking can contribute to several lines of fundamental theoretic development. One line is the identification of fixed hierarchical levels. Another line is the development of definitions of concepts that currently lack consensus such as organism, evolution, major transition, and life. In analogy with how one can use Lego bricks for constructing Lego trains and Lego cities, one can also use the objects that are included in the Operator Hierarchy, the so-called operators, as the theoretical and physical building blocks of all systems that consist of interacting operators.

Reflections by multidisciplinary scientists

Since it represents a new approach, the Operator Theory can profit in many ways from discussion and constructive criticism. For this reason, a broad set of renowned scientists were approached with the request of whether they would like to contribute to this book by writing a review chapter. The many enthusiastic reactions covered a wide range of scientific disciplines allowing for a diverse view on the topics at hand. Each scientist was offered a free choice to write, e.g. a supplementary line of reasoning, a critical analysis, a suggestion for links with existing theory, and an inquiry of the practical utility. The multi-faceted contributions of the specialists have increased the richness, depth, and relevancy of this book in many ways. A first step towards further conversations is set in Chap. 18 in which the editor of this book responds to the remarks of the reviewers.

If you long for order and simplicity, you may enjoy reading this book

While in everyday life things seem to increase in complexity all the time, this book pursues simplicity. In line with this goal, this book attempts to reduce the complexity of its themes to the level of irreducible simplicity. Once a conceptual core of irreducible simplicity has been identified, this is used as a basis for scaling up as well as for generalisation. As a further consequence of striving towards a framework that is based on simplicity, this book is structured in a step-by-step way. Basic concepts are introduced in the first chapters and are used in subsequent chapters to handle more complex situations.

Because it focuses on simplicity and core concepts, this book may offer a rich source for conceptually oriented students and researchers from many different backgrounds, including, for example, biology, ecology, physics, philosophy, system science, social science, economy, astrobiology, and artificial life. Some chapters focus on biological questions, including, for example, the question of how to define the organism concept, the question of how to identify levels of biological organisation and major evolutionary transitions, and the question of how to develop an object-based approach to evolution that may assist in organising the many factors that play a role in the extended evolutionary synthesis. Other chapters focus more specifically on system science, for example by elucidating the Operator Hierarchy, and its utility as a basis for the analysis of ecological and societal processes. One chapter focuses on thermodynamics and on how the dispersion of free energy gradients can not only cause chaos, but also forms the basis for organised matter and organised systems. Several chapters pay attention to philosophical aspects of the concepts that are discussed.

Wageningen, Gelderland, The Netherlands Gerard A.J.M. Jagers op Akkerhuis

Acknowledgements

I am heavily indebted to many friends and colleagues who, in addition to the co-authors and authors of the different chapters, have offered invaluable contributions to the content of this book. Special gratitude goes to the late Frank Veeneklaas (WOT) who was a dear friend of mine and a much appreciated discussion partner. Veeneklaas initiated the writing of the book: "The pursuit of complexity. The utility of biodiversity from an evolutionary perspective," which allowed me to prepare a lot of thoughts that provided a foundation for the current book. Jack Faber and Els Dieleman and my employer Wageningen Environmental Research (Alterra) are thanked for the long-lasting general support of this project. I would also like to thank a broad range of friends who in many important ways have contributed to the current text. Joke Marinissen and Herbert Diemont helped with the introduction. The members of the BKK choir offered a challenging environment for discussions about evolution. Caroline van der Mark, Marnix van Meer and Peter Schippers commented on concept chapters. Marjolein Kikkert shared information about viruses. Albert Ballast provided invaluable information about thermodynamics. Furthermore, I thank Herbert Prins, Geerten Hengeveld, Arjen de Groot, Marieke de Lange, Dick Melman and Judith Westerink for discussions about various aspects of the content of this book. Lawrence Jones-Walters assisted in the phrasing of the title. Daniel Helman helped improving the quality of the text. I much enjoyed the thought exchange about art and evolution with Rudy Klomp, Clasina Douma and Koert van Mensvoort. I am indebted to Hans Peter Willems of Mind|Construct for advanced discussions about artificial intelligence. Bouwine Bergsma is thanked for sharing her thoughts about how to explain evolution to children. Jan Meint Greben introduced me to interesting details of the world of fundamental particles. Atanu Chatterjee and Frank Lambert are thanked warmly for discussions with a focus on thermodynamics and entropy. My daughter Marrit Jagers op Akkerhuis has helped designing some of the figures. While the text in this publication aims at offering an accurate representation of the insights gained from the literature and from discussions with colleagues, any potential misinterpretation is the sole responsibility of the authors. This research was financed in part by the strategic research program KBIV "Sustainable spatial development of ecosystems, landscapes, seas and regions," which is funded by the Dutch Ministry of Economic Affairs.

Last but not the least, I'd like to express my warm thanks to my wife Florentine and our kids, Marrit, Stijn and Inge for the many enjoyable moments that we shared all these years and for tolerating my fervour when yet another fascinating puzzle came along.

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Part II Discussion, Reflections, and Conclusions

Main Contributions by Authors and Reviewers

Gerard A.J.M. Jagers op Akkerhuis is the editor and main contributor to this book. Three of the chapters he wrote were co-authored by his colleagues and friends Hendrik Pieter (Diedert) Spijkerboer and Hans Peter Koelewijn. Gerard is the architect of the Operator Theory and has a long history in biology, ecotoxicology and system science. The contributions of Diedert reflect his background in mathematical modelling and his current work in the field of evolutionary philosophy. With his experience in logical thinking, his capacity to follow through discussions to the finest details, and his quest for precision Diedert has contributed in a major way to many aspects of this book, most notably to the chapter about the Operator Hierarchy. Hans-Peter has been involved in the development of the ideas for this book since 2010. While Hans-Peter has a broad interest, his contributions to this book involved his insights in genetics and plant breeding, genetic conflicts and units of selection.

This book includes a collection of reflection chapters, in which a broad range of scientists was invited to write in-depth reviews. The first reflection chapter was written by Spinoza prize-winning mathematical logician Henk Barendregt, renowned for his contributions to lambda calculus and type theory, which focuses on computability and logic. As the Operator Theory also includes a hierarchy of computable processes, namely when operators of lower levels form operators of higher levels, a reflection by Henk was considered very relevant.

A reflection on the chapter about Darwinian evolution was offered by biologist and evolution scientist Nico van Straalen and philosopher Bart Gremmen. In their reflection they focused on theoretical aspects of the object-based graph pattern of Darwinian evolution. They also posed the question of whether or not the abstract pattern of Darwinian evolution at the smallest scale can still be linked with biological and ecological narratives.

Philosopher of science Thomas Reydon has a background in speciation and evolution. Thomas' reflections enriched this book with an insightful discussion of the concepts of Universal Darwinism and Generalised Darwinism. Thomas also assessed the use of kinds as the nodes in an object-based graph pattern.

In his review the economist and philosopher Jack Vromen draws on his views on evolutionary economics to scrutinise several tenets of the operator-based definition of the organism. Jack winds up defending a gradualist perspective on organismality.

Management scholar and evolutionary social scientist J.W. (Jan-Willem) Stoelhorst has a long-standing interest in the generalisation of evolutionary theory. Jan-Willem contrasts how the Operator Theory identifies transitions in individuality with the notion of transitions in "Major Evolutionary Transitions Theory." He discusses how the Operator Theory's axiomatic approach adds insights over and above the more inductive approach of Major Evolutionary Transitions Theory. In particular, Jan-Willem concludes that the Operator Theory opens up the possibility for a much finer-grained understanding of major transitions than currently offered by Major Evolutionary Transitions Theory.

NASA astrobiologist Michael Russell is renowned for his research and theoretical contributions to the identification of the physicochemical origin of the first cells. When reading the chapter about the definition of life, Michael noticed that there was a lot of attention for the conceptual definition of "life," while comparatively little attention was paid to the process side. This led him to suggest that more attention should be paid to non-equilibrium thermodynamics.

Physicists Georgi Georgiev and Atanu Chatterjee MSc both share a passion for generalising approaches in science based on the principle of least action and thermodynamics. In their reflection they focus on the link between general thermodynamic processes and the need for the formation of closed systems, such as the operators. They also discuss new concepts for linking thermodynamics to the emergence of complexity.

In the discussion section, philosopher Hub Zwart discusses the relevance and profile of the Operator Theory by comparing it to the ideas of Teilhard de Chardin about the dynamics of evolution and noosphere.

Chapter 1
General Introduction

Gerard A.J.M. Jagers op Akkerhuis

> *"… we argue that impactful data-free papers provide coherent syntheses and reviews of current knowledge, integrate different fields of thought in novel ways, or identify important future directions within a framework beyond the scope typical of empirical studies"(Davis et al. 2015).*

1.1 Towards Better Communication

Every day, biologists and other life scientists communicate about their work, using concepts such as organism, ecological hierarchy, life and evolution. In many cases working definitions offer the basis for communication. Because working definitions are constructed in relation to specific goals, they are not always identical. The repeated construction of new working definitions has led to an accumulation of different descriptions. For example, Trifonov (2011) has listed a total of 123 different scientific definitions of the concept of life. The existence of so many different definitions for life and for other concepts, neither leads to smooth communication nor does it offer a solid foundation for the generalisation of theory. Instead, the abundance of working definitions leads to confusion and practical problems. This can be illustrated by the following two recent debates in the scientific literature about what is meant with the concept of an organism and the concept of evolution.

As Pepper and Herron (2008) discuss, defining the organism concept has since long been a theoretical challenge. A consensus definition does not seem to exist. A possible reason for this is that the criteria that are generally used "are necessary for recognising an organism, but not sufficient because they are also met by many non-organisms" (Pepper and Herron 2008). For example spatial unity, which implies having a body (Metz 2013), is frequently suggested as a property of organisms, but it is not a sufficient criterion, because many non-organisms (such a tea-cup or a car) are spatially united as well. Another criterion that has been used for defining

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_1

organisms is that they have DNA. However, a viral strand of DNA also may be viewed as an organism using this criterion. Pepper and Herron (2008) furthermore remark that the criteria for a definition of the organism should answer the central question of "part versus organism versus group". For example, there is uncertainty about whether or not the grouped cells of the slug of a slime mould (e.g. *Dictyostelium discoideum*) represent a multicellular organism, or that such cells represent a colony. Due to non-overlapping or incomplete criteria, one can find many definitions in the literature of which one includes specific entities as organisms, while another excludes the same entities because they are not accepted as organisms. This source of ambiguity has led to many philosophical and practical discussions (e.g. Godfrey-Smith 2009; Szathmáry 2015) but it is still an open question how clarity can be reached about the classification of organisms compared to other objects. To resolve such ambiguity, some researchers have gone as far as suggesting that one should no longer try to define an organism as a unity. Instead one should focus on a degree of organismality that makes use of a select list of properties, each of which can be present to a lesser or higher degree (Godfrey-Smith 2009). Such a solution may work in everyday conversations and possibly also in engineering and applied sciences, but because the necessity of a stringent limit to the organism is denied, it is hard to imagine how such a gradualist approach can be matched with approaches that define the organism as a conceptual class that is linked to a physical unit that has autonomy (Bhaskar 1998; Moreno and Mossio 2015).

Another example of a concept that is much discussed is evolution. The concept of evolution stems from the Latin origin evolvere which means to unroll, or to unfold. Due to the width of this Latin origin, several uses of the concept have entered the vocabulary of science. This has resulted in a range of local and non-overlapping meanings of the term evolution. The first meaning is that of change/unrolling, which is in use for example for physical, astronomical and social processes, such as the evolution of solar systems, or the evolution of culture. The second meaning is that of Darwinian evolution, which is related to descent with modification through variation and natural selection (Darwin 1876, p. 313). In addition to these interpretations, the modern synthesis and the discovery of genetics have stimulated modellers to interpret Darwinian evolution as the change across generations of the allele frequencies in eukaryote populations, or the use of for example plasmid DNA frequencies in bacteria. While the use of such frequencies has created a highly successful foundation for calculations and predictions, it can be questioned from an ontological point of view whether a definition that focuses on a measure for an *outcome* of Darwinian evolution, such as a population based change in DNA/RNA frequencies, can simultaneously be viewed as a definition of the *concept* of Darwinian evolution.

In a world where the interpretation of concepts seems to be subject to regular change, this book aims at contributing to discussions by identifying relatively stable and generally valid definitions of concepts. When using the word general in this context one must not imagine a one size fits all approach. Instead, the goal is to construct definitions that support the development of scientific reasoning that is general in the sense that the specific logic involved can be used in a trans-disciplinary way. This kind of generality is deemed valuable because even when the use of local working definitions may not cause problems in everyday communication, in a broader scientific context local definitions have the effect of building a conceptual railroad on pre-pressed concrete sleepers that have been made with too little cement powder.

1.1.1 An Axiomatic Approach

We suggest that the search for conceptual unification can profit from the way mathematicians create theory. In mathematics, the general attitude towards theory and definitions is one of precision. For example, when asked for the definition of an ellipse, all mathematicians will come up with a close to similar answer. And they would not accept substantial differences when they occurred, because it could lead to dangerous situations if, for example, different outcomes would be possible for the analysis of how strong a foundation one needs for a bridge or a high-rise.

A way of working that has brought much coherence in mathematics is the axiomatic approach, which implies that one starts with simple, given concepts and, from there, defines more complex concepts. The axiomatic approach has a long history in mathematics, starting with Aristotle and applied by Euclid (Elements) and the Philosophiae Naturalis Principia Mathematica of Newton (1687). A decade after the Principia Mathematica was published (Whitehead and Russell 1910, 1912, 1913), Woodger (1937) became an early explorer of whether or not an axiomatic reasoning could be applied in biology. In turn, Woodger's work has influenced for example the mathematico-deductive theory of Hull (Hull et al. 1940). With respect to a population-oriented analysis of evolution, the axiomatic method can also be found in for example the work of Williams (1970, 1973) , Chambers (2002) and Rice (2008).

With respect to axiomatic approaches Williams (1970) has indicated that: "*The axiomatic method and the experimental method are the two pillars on which science is built. A (possibly unconscious) version of the axiomatic method is used whenever reasoning is used, just as a (possibly unconscious) version of the experimental method is used whenever observation is used*."

Interestingly, even though the above citation suggests that reasoning always involves an axiomatic approach, the axiomatic approach is rarely specifically mentioned or applied in publications in the field of the life sciences. This may be one of the reasons why the life sciences are still debating the meanings and definitions of concepts, as is apparent from discussions about Darwinian individuals (Godfrey-Smith 2009) or the extension of the evolutionary synthesis (Laland et al. 2015).

An advantage of an axiomatic approach is that it works from the bottom up and thereby assists in the generation of new hypotheses, the discovery of counterintuitive results, and the creation of theoretical connections between disciplines. By working from the bottom up one naturally starts with a focus on kinds of events that happened first and/or at low levels of organisation, and continues with a focus on kinds of events that happened later and/or at higher levels of organisation. According to such reasoning a tool like a hammer can only exist because intelligent beings have had thoughts about hammering. By the same token, there must first have been cells before these could develop towards multicellularity, and multicellular organisms had to exist prior to the formation of organs inside their bodies. This way of working from the bottom up is viewed in this book as an exciting direction for solving definition problems. But even though an axiomatic approach may assist in seeing the forest for the trees when talking about definitions, there is still a long way to go before an axiomatic approach can be mapped onto all the objects and concepts in the life sciences.

1.2 Contributions by Systems Theory and Philosophy of Science

Because important concepts such as the organism and evolution still lack unanimously accepted definitions, scientists have explored different pathways towards solutions. Maynard Smith and Szathmáry (1995), Queller (1997) and Queller and Strassmann (2009) for example suggested that an entity that shows cooperation of its parts, competition reduction, and reproduction as part of a larger unit, would classify as an organism. Recall that at the same time Godfrey-Smith (2009) has suggested that because of definition problems, it may be better to forget about defining the organism, and instead focus on a degree of organismality. Such a degree is composed of different values for three selected parameters: (1) a bottleneck, referring to the divide between generations, (2) reproductive specialisation, focusing on the separation between soma and germ line and (3) overall integration, referring for example to the dependence of parts and the degree of overall physical unity.

In relation to the work of Kühn (1962), a philosopher of science would probably conclude that the coexistence of the above conflicting ideas about the organism concept indicate that the paradigm of the organism is in a chaotic, transitional state. And that a new paradigm may be needed to end this chaos.

Meanwhile, a system scientist may suggest that it may be possible to identify a combination of properties that all organisms share. A challenge from the perspective of systems theory is the following. To identify organisms and non-organisms one needs criteria. Initially any separation of examplary objects into organisms and things that are not organisms will make use of working definitions, or folk definitions, which are still preliminary. Using such folk definitions, some examples of an organism may be assigned to the non-organism group, and the other way around. For example, would a virus classify as an organism or a non-organism? And how can the slug of a slime mould be classified? Because of ambiguities in the folk definitions, the groups that will be created will not necessarily be uniform, and uncertainty will remain about the accuracy of a definition based on such groups. Thus, as long as one lacks a definition, one cannot create uniform groups, and because there are problems with the formation of uniform groups, it is not possible to deduce a clear definition. On the one hand, a practical solution to such a catch-22 would be to start a process of iterative refinement. On the other hand, a theoretical solution would require the development of a general scaffold that indicates whether or not a specific system is an organism. Importantly, such a scaffold would have to be constructed independently of the criteria that normally are used to determine whether or not a system is an organism.

To deal with the kind of challenges that were just described, both systems theory and philosophy of science adherents adopt philosophical reasoning. Therefore, these two groups of researchers, which now seem to work largely independently, may potentially profit from philosophical cooperation. This topic is revisited in the general discussion chapter of this book (Chap. 16).

1.3 Why Focus on Definitions and Classification?

Definitions and classification are a means to improve communication. If one talks about definitions, however, people sometimes are suspicious. One suggestion is that it is not relevant for practical work to pay much attention to exceptions and marginal cases, as most of the work involves paradigmatic cases. Another suggestions is that instead of focusing on definitions and classification, it would be more scientific, and of greater practical utility to focus on mechanisms and predictions. And it is also suggested that the quest for stringent definitions is a waste of time because there will always be problematic cases. The following paragraphs give room to such considerations.

1.3.1 Why Worry About Marginal Cases?

It is sometimes suggested that as long as an existing definition does not cause a problem it does not need to be improved. This seems to us a matter of position. For example, if one imagines a person who lives near the border of a country, a change in the geographical borderline would make this person an inhabitant of a different country that has different social and economic rules that may be unfamiliar to the person. By analogy, if a specific example is not a paradigm case that sits comfortably in the centre of a class, but lays close to a conceptual borderline, a small change of the classification can have marked consequences. For example both a virus molecule and a cell may be viewed as a living being/organism, because of reproduction. Here the focus is not on ambiguities of using the criterion of reproduction as a hallmark for something being an organism, but instead the focus is on what happens conceptually if one classifies a virus either as a molecule or as an organism. In either case, the decision will imply a package of properties. The assumption that a virus is a molecule would for example imply that experimental work would have to focus on chemistry, and that in test-tube experiments it would be necessary to add polymerase to enable transcription. If a virus would be an organism the adding of polymerase would not be necessary, because an organism can autonomously reproduce its DNA. This example shows that the quality of a classification or definition becomes especially visible at the edges, and may have marked practical implications.

1.3.2 The Value of Definitions When Compared to Predictions

The construction of definitions is sometimes depicted as being of lesser scientific or practical utility than the act of predicting. People who think this way may suggest that their branch of science has developed from a descriptive science to a predictive science, and the latter is seen as of higher scientific value. While there is much practical value in predictions, the activities of defining, describing and predicting are all interdependent when viewed in a broader perspective. For example, in the process of doing research a scientist will at least need some preliminary definitions, or working definitions, which allow for the identification of the objects that are studied, such as honey bees, and the relationships one is interested in, such as the efficiency of the search for nectar. In turn, the objects and relationships thus defined form the foundation for different kinds of classifications, equations and models. Classifications organise entities and/or their properties in categories. Equations describe relationships between variables in a stringent way. Models are entities that represent other entities. Some equations, classifications and models can be used as the basis for predictions. All the steps from definitions to predictions can be viewed as being interdependent. Every next step makes use of all preceding steps, while insights from next steps may sometimes ask for a renewed analysis of entities used in preceding steps. As a result, the accuracy of a prediction depends on the accuracy of the descriptions, definitions, equations etc. The dependency on definitions also implies that if much used concepts have many definitions, their suitability as a foundation for modelling and prediction is cast into doubt.

1.3.3 The Philosophical Basis of Stringent Definitions

> "*… there are many things that philosophy of biology might be. A philosopher might uncover, explicate, and possibly solve problems in biological theory and methodology. He might even go on to communicate these results to other philosophers, to scientists, and especially to biologists. He might show what consequences biological phenomena and theories have for other sciences and for philosophy or to show what consequences other sciences and even philosophy have for biology. These are some of the things which philosophers of biology might do*"(Hull 1969, pp. 178–179).

Like in the work of Hull, the aim of this book is to define and relate scientific concepts. For this purpose insight is needed in the identification and classification of things that exist physically in the world, and things that exist as concepts in the memory of organisms. Concepts can be related to physical things, such as a car, or to imaginary things, such as a unicorn, or a conceptual model. And concepts can either refer to a class or to an instance. For example the concept of a cow, can either represent a class which includes all the cow-like things that a person has ever experienced (either physically or as representations in books, on television etc.) or it can refer to the instance of a specific memory of a unique past experience with a cow of the neighbours named Ann during a sunny afternoon on 24 May 2011. Throughout this book classification is never viewed as a goal in itself, but as a tool for the creation of general theory. And while every method of defining the world has its advantages and disadvantages, the goal of this book is to identify an approach that has relatively many advantages and relatively few disadvantages in the context of creating general and logically consistent theory.

With respect to the analysis of relationships between concepts and actual physical entities the reasoning in this book shows relationships with the philosophical approaches of critical realism (Archer et al. 1998) and transcendental realism which Bhaskar (1998) describes as follows, transcendental realism "*…regards the objects of our knowledge as the structures and mechanisms that generate phenomena; and the knowledge as produced in the social activity of science. These objects are neither phenomena (empiricism) nor human constructs imposed upon the phenomena (idealism), but real structures which endure and operate independently of our knowledge, our experience and the conditions which allow us access to them*" (Bhaskar, in: Archer et al. 1998, p. 19).

Bhaskar thus regards as the objects of knowledge the structures and mechanisms that generate phenomena, and regards knowledge as something that is produced in a social context, during scientific activity. Transcendental realism differs from empiricism (Hume 1738) because the structures and mechanisms themselves are not viewed as phenomena. And it differs from idealism (Kant 1786) because the structures and mechanisms in themselves not viewed as human constructs imposed upon the phenomena. Instead, the structures and mechanisms are viewed as "real structures which endure and operate independently of our knowledge, our experience and the conditions which allow us access to them" (Bhaskar 1998).

The viewpoint that knowledge is something that is produced in a social context, during scientific activity (Bhaskar 1998) shows a close connection with social constructivism, which suggests that much of what people learn about the world is the result of, and is speeded up by, discussions with others about experiences and conceptualizations. It cannot be denied that people's knowledge about the world profits from social interactions. At the same time this insight can be viewed as one side of a coin. The other side of the coin is formed by the existence of objects and the occurrence of processes in the world independent of human observation. A deduction that is sometimes made is the following: (1) knowledge about the world and the classifications of objects in the world is socially constructed, (2) the social contexts for classifications are dependent on perspectives, and these perspectives are dependent of people's goals, which may change over time, (3) as classifications are variable social constructs depending on perspective, it is not possible to describe/classify the world in a consistent/uniform way (Jones 2009). A deduction like this can be looked at in two ways.

On the one hand, many classifications depend heavily on a social context, such as notions of space, place, nature, gender and identity. And the boundaries between the categories male and female are blurred by persons with transgender, bi-gender, pangender etc. behavior and by the existence of intersex individuals. Spatial limits too are occurring in many forms, such as the borders of countries, provinces, regions and backyards. In general, categories like these have flexible and gradual boundaries that are mainly based on how people think about the subject, and on where exactly one decides to draw a line in a gradient. For example the rainbow is said to have different colours, and yet the exact limit between yellow and red, depends on an arbitrary separation of intermediate orange colours.

On the other hand, even when classifications are viewed as social constructs, this does not necessarily imply, from a critical realist perspective, that all class limits are equally relative. For example, one can imagine a hypothetical scale of classifications that depend to a variable degree on social learning and on physical reality. At one end of the scale one finds things that lack a natural structure, such as the classifications of a director or the term cool. The meaning of such concepts depends entirely on the social context and may change over time. At the other end of the scale one finds things that have some kind of natural structure at the basis, such as an atom, a molecule, or a cell. While the understanding of a physical system profits from social interactions, it is the physical existence of such a system that acts as a touchstone for the criteria that can best be used for its description and classification. The suggestion that there really are objects out there with a structure that is independent of conventions, is supported by measurements that are based on different principles. Of course, one cannot know what an atom really "is", because it exists at a level of organisation that is far below that of human reality, and to which one cannot gain direct access. Yet it is possible to describe an atom by means of a model. And even when physical objects in the world are observed from different points of view, and when different models are used to represent such a physical object, one can still produce identical values for parameters of atoms and their parts, such as the number of protons in the nucleus, or the mass and the orbit of an electron orbiting around the atom (Kragh 1999). Meanwhile, more accurate models and measurements will generally lead to increasingly accurate and converging values, and not to increasingly different values. Moreover, the independent existence of physical entities is supported by the observation that most of the universe has formed without human interference. In the words of Bhaskar (1998): "… both knowledge and the world are structured, both are differentiated and changing; the latter exists independently of the former (though not our knowledge of this fact); and experiences and the things and causal laws to which it affords us access are normally out of phase with one another. On this view, science is not an epiphenomenon of nature, nor is nature a product of man."

This book focuses on the identification, in a world full of changing and variable definitions, of some relatively unchanging kinds of organisation. In this context circular interactions can be viewed as being of special value. For example when schoolchildren hold each other's hands and create a circle. The idea is that circular interactions cause a collective state which represents an unchanging property that is typical for a new kind of organisation (this subject is discussed in detail in Sect. 2.4 about closure). Class limits based on circularity can be viewed as relatively unchanging, because changes in the objects that create the closure, will not affect the circularity itself. Meanwhile, the use of closure allows for sharp class limits because at any moment one can either observe a full circularity or an incomplete circularity. Of these two states, the incomplete circularity does not represent circularity. Such reasoning results in abinary classification, based on the presence or absence of the circularity.

In this book it is demonstrated that the binary distinction caused by circularity can be applied both for the identification and for the ranking of objects of increasing complexity, including for example the atoms, the molecules, the cells, and more complex kinds of organisms. The ranking of kinds of objects with increasingly complex "circular" organisation was named the Operator Hierarchy (Jagers op Akkerhuis and van Straalen 1999) and the theory about this ranking and its applications is called the Operator Theory. The Operator Theory basically has limited ambitions, because it primarily aims at the identification and classification/ranking of fundamental building blocks of organisation in nature, called operators. From this basis, however, a more ambitious second step can be envisioned, namely the step towards a system in which the operators serve as the basic building blocks for analysing the organisation of any and all systems that consist of operators.

1.4 Resolving Definition Problems

A likely fundamental requirement for any generalisation of scientific theory is a hierarchical approach to organisation. Such an approach would connect all the different scientific domains in the range from fundamental particle physics, to chemistry, biology and sociology/psychology. A methodology for the identification of hierarchical organisation is a requirement for the identification of basic building blocks of organisation in nature. Once such building blocks have been identified they could be used as the nodes in graphs and as the "agents" in calculations.

What then are the kinds of building blocks that can be used in such generalised approaches? If one looks at existing rankings of building blocks in nature, these frequently include entities of different kinds, such as atoms, organelles, cells, organisms and populations. The Operator Theory (Jagers op Akkerhuis and van Straalen 1999) offers a different hierarchy, in which lower level building blocks construct higher level building blocks, in such a way, that all objects in the sequence can be viewed as building blocks each of which consists in a particular way of smaller building blocks. Based on logic the Operator Theory basically suggests that hierarchy in nature can be analysed along three different axes, namely:

1. A hierarchy of physical objects that have increasingly complex structures, from particles to organisms. The objects in this hierarchy are called operators.
2. A hierarchy of conceptual groups, such as populations and communities. The elements of the groups can be objects, operators or lumps of attached operators.
3. The hierarchy of parts that can be found inside an operator, such as organelles in unicellular organisms, and organs in multicellular organisms.

As the Operator Theory represents a novel approach to hierarchical organisation, several results in this book shed new light on existing theories. For example, Darwinian evolution is generally viewed as a process, but the reasoning in this book leads to the insight that the concept can best be defined as a graph-pattern. Such an outcome may seem counterintuitive, especially since Darwinian evolution since long has been associated with the emergence of new species and other forms of temporal change. What is interesting, however, is that if one defines Darwinian evolution by means of a graph-pattern, this allows one to generalise the pattern in such a way that it can be applied to organisms and to objects from the physical world. Viewing Darwinian evolution this way furthermore offers a foundation for organising major evolutionary transitions in a series of well-defined classes and in this way contributing to the Major Evolutionary Transitions Theory of Maynard Smith and Szathmáry (1995). Interestingly and importantly, the new perspective on Darwinian evolution also suggests a unique pathway towards the prediction of future transitions in evolution. Another innovation is the use of the Operator Theory for defining the concept of the organism. And if one uses the Operator Theory as a foundation one can also demonstrate that by analogy with how the concept of water refers to a molecule and a fluid, also the concept of life can be defined in two different ways, either as a property of organisms, or as referring to a system of interacting organisms.

1.4.1 Guiding Principles

This book can be viewed as one more step towards a coherent theoretic framework for biology and related life sciences. Such goals imply a focus on logical analyses, and logical coherence. Such logical analyses may in the future form a starting point for formalisations that make use of mathematics. While focusing on logical analyses, the subjects discussed in this book will bring together a broad range of perspectives including philosophy, ontology, biology and ecology, evolutionary science, and physics.

The resolution of definitional problems is an important topic of this book. Therefore the reader is offered an explanation of the principles that are used in this book to work towards such a goal. The principles that are used throughout this book as guidance towards generally applicable and logically coherent definitions are:

1. A definition is a language filter based on criteria which allow the select inclusion of relevant cases and the select exclusion of irrelevant cases. One must always check such criteria in both directions. For example a definition which states that a bird is something that uses its wings to fly fails with respect to both criteria. Firstly, there exist things that use wings to fly but are not birds, such as bats and airplanes. Secondly, there exist birds that have wings but do not fly, such as the kiwi and ostrich. The criteria that fully define a concept are named the demarcation criteria. If all relevant cases are included by the criteria, and all irrelevant cases are excluded, the criteria are said to be necessary and sufficient and the definition is said to be intentional. If this is not required or intended, what results is a working definition that people use because they have agreed on the definition for the occasion. Finally, a stipulative definition introduces a completely new concept and related criteria.

2. Ockham (c. 1287–1347) phrased a law of parsimony, which has become known as Ockham's razor (also referred to as Occam's razor). This law states that if there is a choice between competing theoretical tools (such as hypotheses, definitions or predictions) that are equally successful in their performance, one must select the option with the fewest assumptions. By the same token, if two theories have equally many assumptions, the theory should be preferred that explains the largest number of observations and/or does so in the most coherent way. The relevance of Ockhams razor for science is stressed by Ellis (2010) stating that: "I cannot overemphasise the importance of Occam's razor to the practice of science. If you abandon this principle, you might as well believe any interpretation of the world that you find comforting and appealing ..."
3. As an extension of Ockham's razor one can also accept that a theory that has a wider scope also has additional criteria, as long as just so many criteria are added as are required for the increased generality. An example of this principle is the information that Einstein's theory added to Newton's theory, thereby creating an approach that covered a broader field of examplary cases. A famous statement of Einstein about combining simplicity and comprehensiveness is relevant: "*It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience*" (Einstein 1934, p. 165).
4. A combination of definitions should not lead to a logical loop. An example of a logical loop is given by the following pair of definitions. The first definition tells that the organism is a contiguous living system. And the second definition tells that life is a characteristic distinguishing physical entities having biological processes from those that do not. The construction of entities having biological processes can be viewed as pointing back to the organism concept (because only organisms carry out biological processes), hereby closing the logical loop from the organism, to life, and back to the organism.
5. Concepts that are used in a definition must themselves also be conceptually anchored. This book distinguishes between three kinds of conceptual anchoring.

   (a) When the anchoring starts with simple objects/concepts and works towards complexity, the method is viewed in this book as working from the bottom up. By working from the bottom up logical loops can be avoided. An example of a bottom-up definition would be to say that an apple is the fruit of a plant of the genus Malus.
   (b) In addition to anchoring from the bottom up, one can also distinguish the possibility of level anchoring. An example of level anchoring is the indication of the colour yellow as referring to the visual impression that people generally have when observing wavelengths in between (roughly) 577 and 597 nanometres. Another example of level anchoring is the description of an apple as a fruit that is round, yellow or greenish, and that has a sweet–sour taste. The fact that not every apple is round, and that not every round thing is an apple, indicates that level anchoring does not automatically lead to necessary and sufficient criteria.

(c) Anchoring can also focus on a particular object, and identify things that are parts of it. This kind of anchoring is viewed as approaching organisation from the top down. An example of a top down method is the choice to use an apple as the top level, and to distinguish the skin, the core and the seeds inside the apple. In cases such as an apple the level that one starts with will be defined by means of level anchoring. In such cases, the anchoring views the highest level as a primitive concept. A more complete anchoring can be created by defining the kind of object at the highest level from the bottom up, viewing an apple as a fruit of a plant of the genus Malus, and by continuing from that point with anchoring from the top down.

The above principles reflect in part Newton's (1729) fundamental rules of scientific reasoning (which Newton referred to as natural philosophy). Newton's rules (represented here without Newton's explanations) focus on Ockham's razor (rule 1), on the generality of theory (rule 2, rule 3), and on the application of the scientific method (which is discussed in Chap. 16).

"Rule 1: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

Rule 2: Therefore to the same natural effects we must, as far as possible, assign the same causes.

Rule 3: The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.

Rule 4: In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, not withstanding any contrary hypothesis that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.

1.5 Subjects Discussed in this Book

The contributions of this book to ontology and systems theory are structured in pairs of chapters. Every first chapter of such a pair introduces a new way of looking at an existing definition, and the questions that accompany such a definition. The second chapter of the pair offers a reflection on the matter by a specialist in the field. The specialists were asked to offer independent analyses and viewpoints.

Apart from a general introduction and a general discussion, this book contains seven chapters which deal with different aspects of the following concept/theories in science:

- The Operator Theory, a contribution to the ontology of hierarchy.
- A graph-pattern for Darwinian evolution at the smallest scale.
- Extending the smallest scale graph-pattern for Darwinian evolution.
- Major evolutionary transitions that lead to operators.

- Major evolutionary transitions that lead to interaction systems.
- Defining life by analogy with water.
- Thermodynamics and the emergence of organised matter.

The following paragraphs summarise why these concepts are discussed and how this book contributes to their definitions.

1.5.1 The Operator Hierarchy (Chaps. 2 and 3)

Classically, the concept of hierarchy has been approached as a tripartite logic, based on the levels of part, object and world. By stepping up this ladder one zooms out, and a new larger world can be selected, after which the old world becomes an object, and the old object becomes a part. In an inverse process, one can step down the ladder. By stepping up or down this ladder, a hierarchy can be created that connects many different levels.

The reasoning of this book aims at advancing on the classical approach of dealing with hierarchy. One aspect for which innovations are suggested is that the classical approach offers no commonly accepted rules for what is meant precisely with an object or a part. As a consequence, there are no stringent rules for the identification of a higher or lower level. As a result, many different hierarchies can be, and have been constructed. In turn, the existence of many different hierarchies leads away from the scientific goal of generality.

A second contribution to the classical approach is that the Operator Theory can solve the problem that the classical approaches amalgamate material entities and conceptual entities of different kinds. As an example one can study the kinds of objects involved in the following ranking: cell, organism, population and planet.

Without prior knowledge, the term cell may either refer to a separate cell (now the cell is an organism) or to a cell inside a multicellular organism (where the cell is not an organism, but a part). In both interpretations the term cell refers to a material entity. At one higher level one finds the organism. This term refers to many different kinds of organisation ranging from bacteria to elephants. In other words, the organism concept refers to a very broad ontological class, not to any specific kind of material entity. As the organism concept also applies to any single celled organism, the position of organism in the example ranking is ambiguous. The level above the organism is that of the concept of the population. According to the Operator Theory, a population is not viewed as a material object, but as a theoretical indication of a select group of objects. Finally, a planet represents a material object, but of a different kind than a molecule and a bacterial cell. These analyses indicate that the ranking in the example mixes material objects of different kinds and conceptual classes of different kinds. As some elements of the ranking are material, and others conceptual, and because different kinds of ranking rules have been used for defining different levels, it can be concluded that the ranking is not based on similar kinds of concepts/entities/ranking rules, which is problematic from the perspective of logical coherence.

To go beyond these limitations the Operator Theory (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2001, 2008, 2010a) is based on a ranking in which material building blocks, the operators, of a low level give rise to operators of ever higher levels, in a step-by-step way. Examples of operators at different levels of organisation are for example atoms, molecules, cells, and multicellulars. Sections 2.5 to 2.7 present a discussion of how this step-by-step construction process offers a foundation for innovations in the field of ontology. The operator concept, and the hierarchy of the operators can be used as a foundation for the analysis of the organisation in any system that consists of operators.

1.5.2 Defining the Concept of Darwinian Evolution (at the Smallest Scale) (Chaps. 4 and 5)

The conventional literature about Darwinian evolution has become tightly associated with the modern evolutionary synthesis. Both the modern synthesis (Huxley 1942), and its recent extension named the extended synthesis (Pigliucci and Rausher 2007; Pigliucci and Müller 2010; Laland 2015; Laland et al. 2015), have proven to be successful tools for organising the factors that contribute to evolution and for modelling quantitatively the changes in fractions of organisms with specific properties in populations. The stringent focus on populations can be viewed as a response to sexual reproduction and the exchange of alleles, which can best be handled by the calculation of allele/DNA fractions in large numbers of objects.

From a philosophical/ontological perspective, it is relevant to remark that a definition of change in population-based frequencies of DNA/alleles differs in kind from a definition of the concept of evolution. There are two aspects that support this remark. The first aspect focuses on ontological kinds. If one defines Darwinian evolution as a change in frequencies of DNA/alleles, this implies that one focuses on the difference between a preceding and a current frequency. A question that can now be asked is whether a difference relationship can accurately represent the concept of evolution when it makes use of frequencies when such frequencies imply that one can no longer zoom in on the relationships between a specific mother and her specific offspring. As it is no longer possible to zoom in on such relationships, one loses track of the underlying processes such as reproduction, variation and selection. The second aspect focuses on the goal of defining Darwinian evolution in a general way. If a definition focuses on frequencies of DNA or alleles, such a focus will bias evolutionary thinking towards entities with DNA. In principle this bias can be overcome by translating the approach, and also accepting the use of other properties of organisms, or of other entities.

From a philosophical/ontological perspective, a definition of a *measure* for change in DNA/allele frequencies cannot be used as a definition of the *concept* of Darwinian evolution. This implies that even though it has a marked practical utility to define evolution as a measure for change, there is still a need for a philosophical definition that helps defining what the concept of Darwinian evolution means.

In relation to the need for a philosophical definition of Darwinian evolution, a stringent object-based approach is elaborated on in Chap. 4. It will be demonstrated that the conceptual core of Darwinian evolution can be defined by means of a graph-pattern. The smallest scale (individual based) graph pattern will be viewed as a minimal representation of the concept of Darwinian evolution. By recasting Darwinian evolution from a process to a graph-pattern, a range of new opportunities is created. One of the opportunities is that it now becomes very easy to prove when Darwinian evolution has occurred and when it did not occur. Moreover, the new approach makes it easy to generalise the concept of Darwinian evolution to applications inside and outside biology.

1.5.3 Generalisations Based on Darwinian Evolution at the Smallest Scale (Chaps. 6 and 7)

There exist unimaginably many object-based graph-patterns. To make sure that a specific pattern represents the Darwinian kind of evolution, a reference is needed. The suggestion is that as such a reference one can use the smallest scale Darwinian graph-pattern. A relevant advantage of a smallest scale graph-pattern is generality. It fits to a biological approach if one chooses organisms as the nodes of the graph and reproduction as relationships. But the smallest scale graph-pattern can also be generalised to other uses if one fills in other objects and other processes. Chapter 6 will describe how a smallest scale graph pattern can be linked to a broad family of patterns of Darwinian evolution. Examples of such patterns are: Darwinian evolution across multiple generations, Darwinian evolution of developmental histories, Darwinian evolution of kind-based patterns, sexual reproduction, and Darwinian evolutionary patterns based on thoughts. In theory, the entire family of all different patterns defines the field of generalised Darwinism.

1.5.4 Transitions in Complexity that Lead to Objects (Chaps. 8 and 9)

Based on the combination of the Operator Theory and Darwinian graph patterns, several contributions can be made to the theory of Major Evolutionary Transitions.

Major Evolutionary Transitions theory revolves around the combination of the following triptych of criteria: cooperation, competition reduction, and replication as parts of a larger unit after a transition (Maynard Smith and Szathmáry 1995). Through the use of these criteria it has become possible to apply Major Evolutionary Transitions theory to a very broad range of transitions. These criteria are necessary aspects of all major transitions in biology, but they exclude transitions outside biology that do not involve replication, while in biology they allow for the inclusion of transitions of very different kinds (e.g. from cell to organism, and from bee to bee colony). The latter can be viewed as a source of ontological ambiguity.

When looking at the cell–organism and bee–colony transitions, the three functional criteria of Major Evolutionary Transitions theory are insufficient for recognising that a multicellular organism and a colony are not of the same ontological kind. A multicellular organism, such as a bee, is a material object with a single body, while a colony involves many bees flying in and out of a hive. The bees with their hive do not form a body, but can only conceptually (not materially) be viewed as a single entity. As discussed in Chaps. 8 and 10 the Operator Theory suggests that the Major Evolutionary Transitions theory can be supplemented by the addition of structural criteria.

1.5.5 Transitions in Complexity that Lead to Interaction Systems (Chaps. 10 and 11)

The Operator Theory furthermore contributes to the analysis of major transitions that lead to systems of interacting operators, named interaction systems. Examples of transitions that lead to interaction systems are the cooperation of bees in a colony, and the cooperation of cells that form the slug of a slime mould.

The class of interaction systems can be subdivided into many subclasses. Here two subclasses are highlighted, which are deemed of special importance. One subclass is that of the compound objects. Compound objects consist of physically attached operators. An example of a compound object is a stone, or a house, or a log of dead tree, or a floating coconut with mussels attached to it. The other subclass is that of the behavioural groups. A behavioural group is a conceptual unity, based on select behavioural relationships between organisms. Examples of behavioural groups are: a pack of wolves, a population, a community, and a company.

The goal of Chap. 10 is to contribute to the classification of transitions that lead to interaction systems. For this purpose, a decision tree is suggested that is based on the integration of three different kinds of criteria. The first criterion that is used follows the fraternal and egalitarian interactions proposed by Queller (Queller 1997, 2000; Queller and Strassmann 2009). The second kind of criterion makes use of the newly introduced concepts of democratic and centralised coding. And the third kind of criterion invokes the structural classification of the Operator Theory (operators, compound objects and interaction groups) and is meant to transcend the limitations resulting from a select use of functional criteria. The application of these three criteria helps to resolve ambiguities about pluricellular organisations, symbioses and herds.

1.5.6 Defining the Concept of Life (Chaps. 12 and 13)

Defining the concept of life has proven to be a challenging intellectual puzzle. Many different approaches have been suggested for defining life (reviews for example by Morales 1998; Popa 2004; Bedau and Cleland 2010). All these approaches can be linked to different schools of thought. The opinions of scientists in such schools vary considerably. On the one hand there are scientists suggesting that life cannot be defined (Emmeche et al. 1997; van der Steen 1997; Hengeveld 2010; Machery 2012; Cleland 2012). On the other hand, there are scientists who in different ways have tried to construct a definition. For example Koshland Jr. (2002) has suggested a definition based on generalised concepts indicated as the pillars of life. Trifonov (2011) has based a definition on the words that occurred most frequently in existing definitions. Gánti (1971) relates life to its origin, represented by a single cell. Deamer and Fleischaker (1994) suggest that life is a chemical system capable of Darwinian evolution. And Jagers op Akkerhuis (2010b, 2012) has based a definition of life on the Operator Theory suggesting that life is a general term for the presence of dual closure in organisms, while organisms are defined as all operators that are at least as complex as the cell.

With the aim of identifying an approach which can bring consensus in the field, Chap. 12 discusses the idea of defining life by analogy with water. The life–water analogy has been mentioned for example by Benner et al. (2004). And Cleland (2012) has pointed out that molecular theory has offered the necessary foundation for defining a water molecule, while a comparable organic theory is needed as the foundation for defining a life particle. In Chap. 12 the focus is on how chemical theory allowed water to be defined at two levels: (1) water: a molecule with specific properties, and (2) water: the liquid that emerges when many water molecules interact. It is shown that by analogy the concept of life can be defined at two levels: (1) the level of organisms, and (2) the level of the ecosystem. It is shown that these two definitions of life cannot be merged, because the concepts they define represent different ontological kinds.

1.5.7 A Thermodynamic Account of the Emergence of Organised Matter (Chaps. 14 and 15)

Thermodynamics is a broad field of study. Principally it is concerned with the dispersal of energy in space. The concept of entropy is used as a measure for the dispersal of energy. The second law of thermodynamics now states that any process will lead to an increase of the overall entropy of the universe. A statement like this suggests that the overall chaos in the universe will increase. Interestingly, the idea that chaos must increase leads to a puzzling situation if one focuses on the increase in complexity and size of organisms during their lives, and if one analyses the emergence of increasingly complex organisations over time, from unicellular organisms, to endosymbiont cells, to multicellular organisms, and organisms with brains.

Looking for a solution to the above puzzling situation, it is thought interesting to analyse the relationship between thermodynamics and the Operator Theory. Swenson (1988) has discussed the different pathways available to the production of more entropy using the example of a cabin in a mountain region. It was suggested that the heat in the cabin could equilibrate with the cold outside, through different pathways, such as the walls of the cabin, or the windows. The question that is asked in the chapter is which “windows” exist in nature that allow for new pathways for the dispersal of energy? It is discussed in what way the different kinds of operators can be viewed as such windows.

An important discovery has been that thermodynamics can be expressed by means of hypothetical overviews of all the states that can be accessed by the objects in a system. Such states are named accessible microstates. Based on such microstates, the reasoning in this chapter explores the number of states the human DNA and the human brain can be found in. And microstates are also used to analyse the likelihood of the occurrence of the pattern of Darwinian evolution.

1.6 Enjoy Reading this Book

Together, the chapters of this book, and the multidisciplinary reflections and comments on these chapters by independent specialists, offer you a broad range of viewpoints on a selection of fascinating philosophical innovations. Just like a journey starts with the first step, the next chapter introduces you to the Operator Theory, and in this way provides you with a theoretic foundation for analyses and discussions in later chapters.

References

Archer M, Bhaskar R, Collie A, Lawson T, Norrie A (1998) Critical realism. Essential readings. Routledge, London

Bedau MA, Cleland CE (2010) The nature of life: classical and contemporary perspectives from philosophy and science. Cambridge University Press, Cambridge

Benner SA, Ricardo A, Carrigan MA (2004) Is there a common chemical model for life in the universe? Curr Opin Chem Biol 8:672–689

Bhaskar R (1998) Critical realism. Essential readings. Routledge, London

Chambers R (2002) The evolution of Darwin’s theory into an axiomatic system. http://www.math.ups.edu/~bryans/Current/Journal_Spring_2002/213_RChambers_2002.pdf

Cleland C (2012) Life without definitions. Synthese 185(1):125–144. doi:10.1007/s11229-011-9879-7

Darwin C (1876) On the origin of species by means of natural selection, or he preservation of favoured races in the struggle for life, 6th edn. John Murray, London

Davis GH, Payne E, Sih A (2015) Commentary: four ways in which data-free papers on animal personality fail to be impactful. Front Ecol Evol 3:23. doi:10.3389/fevo.2015.00102

Deamer DW, Fleischaker GR (eds) (1994) Origins of life: the central concepts. Jones & Bartlett, Boston

Einstein A (1934) On the method of theoretical physics. Philos Sci 1:163–169.

Ellis RJ (2010) How science works: Evolution - a student primer. Springer.

Emmeche C, Køppe S, Stjernfelt F (1997) Explaining emergence: towards an ontology of levels. J Gen Philos Sci 28(1):83–117. doi:10.1023/A:1008216127933

Gánti T (1971) The principle of life (in Hungarian). Gondolat, Budapest.

Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford.

Perspect Biol Med 18(2):179–184. doi:10.1353/pbm.1975.0005

Hengeveld R (2010) Definitions of life are not only unnecessary, but they can do harm to understanding. Found Sci 16:323–325

Hull D (1969) What philosophy of biology is not. Synthese 20(2):157–184. doi:10.1007/BF00413784 .

Hull CL, Hovland CL, Ross RT, Hall M, Perkings DT, Fitch FB (1940) Mathematico-deductive theory of rote learning. A study in scientific methodology. New Haven, CT: Yale University Press.

Hume D (1738–1740) Treatise on human nature. London.

Huxley JS (1942) Evolution: the modern synthesis. Harper, New York

Jagers op Akkerhuis GAJM (2001) Extrapolating a hierarchy of building block systems towards future neural network organisms. Acta Biotheor 49:171–189

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organization of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2010) Towards a hierarchical definition of life, the organism, and death. Found Sci 15:245–262

Jagers op Akkerhuis GAJM (2010a) The operator hierarchy, a chain of closures linking matter life and artificial intelligence. Ph.D. Thesis, Radboud University, Nijmegen

Jagers op Akkerhuis GAJM (2012) The role of logic and insight in the search for a definition of life. J Biomol Struct Dyn 29:619–620

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego-bricks of nature: evolutionary transitions from fermions to neural networks. World Futures J Gen Evol 53:329–345

Jones R (2009) Categories, borders and boundaries. Prog Hum Geogr 33(2):174–189. doi: 10.1177/0309132508089828

Kant (1786) Metaphysical foundations of natural science. Riga, J.F Hartknoch.

Koshland DE Jr (2002) The seven pillars of life. Science 295(5563):2215–2216. doi:10.1126/science.1068489

Kragh H (1999) Videnskab og virkelighed. Aktuel Naturvidenskab Århus 1:36–38

Kühn TS (1962). The structure of scientific revolutions. University of Chicago Press, Chicago

Laland KN (2015) On evolutionary causes and evolutionary processes. Behav Process 117:97–104. doi:10.1016/j.beproc.2014.05.008

Laland KN, Uller T, Feldman MW, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J (2015) The extended evolutionary synthesis: its structure, assumptions and predictions. Proc Biol Sci 282(1813):20151019

Machery E (2012) Why I stopped worrying about the definition of life… why you should as well. Synthese 185:145–164

Maynard Smith J, Szathmáry E (1995) The major transitions in evolution. Freeman, Oxford

Metz JAJ (2013) On the concept of individual in ecology and evolution. J Math Biol 66:635–647. doi:10.1007/s00285-012-0610-1

Morales J (1998) The definition of life. Psychozoan 1(a strictly electronic journal):1–39.

Moreno A, Mossio M (2015) Biological autonomy: a philosophical and theoretical enquiry. Springer, Dordrecht, The Netherlands

Newton I (1687) Philosophiae Naturalis Principia Mathematica. Jussu Societatis Regiæ, London

Newton I (1726) Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy), 3rd edn. William & John Innys, London

Pepper JW, Herron MD (2008) Does biology need an organism concept? Biol Rev 83(4):621–627. doi:10.1111/j.1469-185X.2008.00057.x

Pigliucci M, Müller GB (2010) Evolution—the extended synthesis. The MIT Press, Cambridge, MA

Pigliucci M, Rausher M (2007) Do we need an extended evolutionary synthesis? Evolution 61(12):2743–2749. doi:10.1111/j.1558-5646.2007.00246.x

Popa R (2004) Between necessity and probability: searching for the definition and the origin of life. In: Advances in astrobiology and biogeophysics. Springer-Verlag Berlin, Heidelberg

Queller DC (1997) Cooperators since life began. Q Rev Biol 72(2):184. doi:10.1086/419766

Queller DC (2000) Relatedness and the fraternal major transitions. Philos Trans R Soc Lond B Biol Sci 355(1403):1647–1655. doi:10.1098/rstb.2000.0727

Queller DC, Strassmann JE (2009) Beyond society: the evolution of organismality. Philos Trans R Soc Lond B Biol Sci 364:3143–3155

Rice SH (2008) A stochastic version of the Price equation reveals the interplay of deterministic and stochastic processes in evolution. BMC Evol Biol 8:262.

Swenson R (1988) Emergence and the principle of maximum entropy production: Multi-level system Meetings of the International Society for General Systems Research, 32: Theory, evolution, and non-equilirium thermodynamics. Proceedings of the 32nd Annual Meeting of the Internationa Society for General Systems Research

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. Proc Natl Acad Sci, USATrifonov EN (2011) Vocabulary of definitions of life suggests a definition. J Biomol Struct Dyn 29:259–266

van der Steen WJ (1997) Limitations of general concepts: a comment on Emmeche's definition of "life". Ultimate Reality Meaning 20:317–320

Whitehead AN, Russell B (1910) Principia mathematica 1, 1st edn. Cambridge University Press, Cambridge, JFM 41.0083.02

Whitehead AN, Russell B (1912) Principia mathematica 2, 1st edn. Cambridge University Press, Cambridge, JFM 43.0093.03

Whitehead AN, Russell B (1913) Principia mathematica 3, 1st edn. Cambridge University Press, Cambridge, JFM 44.0068.01

Williams MB (1970) Deducing the consequences of evolution: a mathematical model. J Theor Biol 29(3):343–385. doi:10.1016/0022-5193(70)90103-7

Williams MB (1973) Falsifiable predictions of evolutionary theory. Philos Sci 40(4):518. doi:10.1086/288562

Woodger JH (1937) The axiomatic method in biology. Cambridge University Press, Cambridge

Part I
The Operator Theory and Its Applications

Chapter 2
Introducing the Operator Theory

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> "*It seems to be felt in some quarters that the deliberate use of a technique of theorizing involves* (*in the case of biology*) "*fitting the facts of life*" *into some rigid predetermined scheme. Nothing could be further from the truth. Far from making facts conform to a scheme* (*which in any case would be impossible*) *we deliberately construct the theoretical system in such a way that it will as faithfully represent the facts as possible*"
>
> (Woodger 1939, p. 74).

Abstract The Operator Theory is a new theory about the hierarchical organisation of complexity in nature. The theory is based on the idea that in the space of all possible processes, a small subset exists of highly specific processes through which small objects can integrate to form new, more complex objects. The Operator Theory focuses on this small subset of objects. The processes that the Operator Theory focuses on are referred to as uniform closure of the structural and functional kind. The combination of such closures is called a dual closure. Based on dual closures, and in a step by step way, the Operator Theory identifies a branching hierarchy of kinds of objects that have increasingly complex organisation. Any object of a kind that is included in this hierarchy is called an operator, and the branching hierarchy is called the Operator Hierarchy. Interestingly, there are strong indications that, in analogy with the primary and secondary structure of amino acids, the Operator Hierarchy has a secondary structure. The Operator Theory hypothesises that this secondary structure offers a means to one day predict the structure of future kinds of operators. By offering a stringent classification of the operators of different kinds, from quarks to multicellular animals, the Operator Theory can be used to contribute to discussions about fundamental concepts in science, e.g. individuality, organismality, hierarchy, life and (the prediction of) evolution.

The original version of this chapter was revised. An erratum to this chapter can be found at DOI 10.1007/978-3-319-43802-3_20

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DOI 10.1007/978-3-319-43802-3_2

2.1 Introduction

2.1.1 Why Was the Operator Theory Constructed?

The classical literature about ecological/natural hierarchy offers many different rankings of hierarchy in nature that are based on levels of organisation, or levels of complexity, and that include for example atoms, molecules, organelles, cells, organisms, populations and ecosystems (e.g. von Bertalanffy 1950; Feibleman 1954; Salthe 1985; Simon 1962; Koestler 1967; Jaros and Cloete 1987; Alvarez de Lorenzana 1993).

The above literature offers three dominant classical concepts for analysing hierarchical relationships: meronomy, taxonomy and emergence. Meronomy describes how large physical objects have smaller parts, which in turn can have smaller parts etc. An example of a meronomy is a horse which has a heart that between other things consists of muscles, which in turn consist of muscle cells etc. The second concept, taxonomy, describes conceptual subsets that can be identified inside a larger set. An example of taxonomy is the set of all animals, which includes the set of mammals, which includes the set of dogs etc. The third concept, emergence, focuses on how new systems/objects are formed from the interactions between existing objects. An important aspect when focusing on emergence is that modules, aggregates, or assemblies can scaffold further steps. It is exemplified in Simon's (1962) story about the watchmakers Hora and Tempus indicated, and indicates that existence of modules is an important factor in emergence. From the story: The watchmaker Hora put together his watches from smaller, stable modules. Meanwhile, Tempus worked without using modules. When they were disturbed, Hora had only to rebuild the most recently constructed module. The unfortunate Tempus had to restart the entire assembly of his watch from scratch.

If the aim is to create a stringent hierarchical ranking, one should in principle either use taxonomic rules, meronomic rules, or emergence. And one should stick to the kind of entities that fit the selected rule. Meronomy should include only physical objects. Taxonomy should be based selectively on abstractions called sets, or groups. And emergence should focus on interactions between physical objects.

The demand to focus on a single rule and a single kind of entities is not always respected by classical approaches to hierarchy in nature. To further explore this failing we investigate an example-ranking from atom, to molecule, to organelle, cell, organ, organism, population and ecosystem. The steps of ranking from an atom to an organ and then to an organism can be viewed as ranking ever larger physical parts inside a multicellular organism. Here one can recognise a meronomic ranking inside the organism. The difficulty arises with the term organism. The organism concept is included as a single level, while it refers both to a single physical organism, and to a class that includes all organisms, e.g. a bacterial cell and an elephant. And "above" the organism the ranking shifts its focus from physical objects to conceptual grouping, e.g. populations and ecosystems, which represents a taxonomic approach. As the same ranking includes both meronomic and taxonomic aspects it can be viewed as a mixed approach.

Another aspect of the use of methods such as meronomy—is a part of—and taxonomy—is a kind of—is that such methods start from a specific highest level; they work from the top down. For example, inside a molecule one finds parts called atoms. And of all the animals, a special subset is formed by the dogs. Such a top down perspective does not fit well if the aim is to explain the formation of complexity from the bottom up. For example, one cannot start with an atom and say that a molecule is a part of it. And neither can one start with an atom and say that a molecule is a kind of atom. If the aim is to work from the bottom up, a methodology is needed that is based on emergence and the stability of aggregates such as was proposed by Simon (1962). The wish to construct a conceptual framework based on emergence, that creates a hierarchy of objects that are all formed from the bottom up, became the starting point for the Operator Theory.

While working from the bottom up the Operator Theory had to start with defining low complexity concepts/objects, and uses these as a theoretic foundation for defining more complex concepts/objects. The idea was to create an unbroken chain of theoretic steps, in which ideally every next object/definition is based on already established objects/definitions. The idea that theory must be constructed from the bottom up also can be found in so-called axiomatic approaches in mathematics (Whitehead and Russell 1910, 1912, 1913) and biology (Woodger 1937; Nicholson and Gawne 2014).

The Operator Theory's primary goal thus became the identification and ranking of the building blocks in nature, from the small to the large. Since the Big Bang, increasingly complex building blocks have been formed, such as quarks, hadrons, atoms, cells, cells with endosymbionts, multicellulars, and multicellulars with brains. Based on the idea that each of these special building blocks can be viewed as to operate as a single, countable material unit in its environment, the term *operator* was chosen as a generic name for these building blocks (hence the name Operator Theory). The Operator Theory thus aims at understanding the sequential formation of operators and to analyse this sequence as a special aspect of ontogenesis in the universe. As a secondary goal, the Operator Theory also aims at the description of any material entity in the universe in terms of operators. To achieve these two goals, the Operator Theory had to start with the smallest, lowest complexity objects in nature, which according to current knowledge are the fundamental particles that are studied by particle physicists, out of which all matter in the universe is eventually constructed.

Moreover, it was a goal of the Operator Theory to identify, for every step in the sequence starting with quarks, logical criteria which could offer justification for why a particular kind of system actually represented a next kind of operator. Such criteria should also indicate why this kind of system, and not any other kind, could be accepted as the right kind for the next rung on the complexity ladder.

2.2 Introducing Systems and Objects

As a basis for explaining the Operator Theory in the next chapter two concepts need to be explained beforehand: system and object. Interestingly, the concept of a system has proven rather difficult to define, possibly as the result of its many different applications and interpretations. In some schools of thought, a system is viewed as a synonym for a group of entities that show relationships. Now many things can be a system, e.g. a house, a herd of cows, and the earth. Other approaches are more specific and define a system as something that produces its own limits. Now one could think of an organism, or a soap bubble. Still other schools view a system as an arrangement of things which are arranged such that they help someone to accomplish a specified task. Examples of the latter are an education system, or a factory. Still others speak about systems of interacting agents as complex adaptive systems. In the next paragraph we try to identify a common denominator of all these system concepts.

2.2.1 Existing Ideas About Systems

When talking about a system, it is important to realise that the concept system represents an abstraction that is man-made and that generally will be imprecise to some degree. That a system always is a man-made model has already been indicated by Bernard (1865) who suggested that "les systèmes ne sont pas dans la nature mais dans l'ésprit des hommes", which says that systems do not exist in nature, but only in the minds of humans. With his statement, Bernard emphasised that humans use their conceptual powers to view chosen objects and chosen relationships in an integrated way as a system. In mathematics such a system of chosen objects and chosen relationships is called a structure. The viewpoint that systems consist of consciously selected objects and relationships can also be found in Checkland and Scholes (1990, p. 22) who in their book about soft systems methodology emphasise that it is "perfectly legitimate for an investigator to say "I will treat education provision *as if it were a system*", but that is very different from declaring that it *is* a system. This may seem a pedantic point, but it is an error which has dogged system thinking and causes much confusion in the systems literature". The reason why Checkland and Scholes (1990) call their approach soft systems methodology is that the process of enquiry itself can also be analysed in a systemic way, so to speak as a "soft" system.

2.2.2 The Role of Objects in a System

When reasoning about a system, the objects in the system have so far only implicitly been included. Yet objects are important, because any systemic analysis presupposes that it is possible to identify objects and their relationships. This leads to the question of how one can determine whether something is viewed as a system or as an object. To answer this question, the Operator Theory suggests using the same strategy as when defining a system, but now with a focus on the intention to wilfully view an entity as an object, instead of as a system. To view an entity as an object, one must thus make a wilful choice, i.e. the classification is taken as an axiom. Given an object oriented viewpoint, a teacup, an ecosystem, a soil layer, a distant galaxy with millions of stars that are part of it or an imaginary unicorn all can be viewed as objects in one's reasoning. For each object, one must select criteria that allow the identification of the objects' limits. Such criteria can for example be made dependent on functional aspects, such as a specific horizon in a soil where litter is degraded, and on structural aspects, such as when children dance and create a circle-object by holding hands with their neighbours.

2.2.3 Systems and Objects in this Book

In summary, when discussing systems/objects in this book, the following things are relevant.

- Both a system and an object are viewed as wilful selections. When selecting an object one only needs to decide on the limit of the object. The process of selecting a system is more demanding because it requires: (1) A selection of criteria that limit the volume/edge/extent of the system, (2) A selection of criteria for the identification of different objects inside the volume, and (3) A selection of criteria for relationships between objects that are part of the system that are viewed as being relevant.
- Both an object and a system are subsets of a larger world. This implies that the environment of a system or object is naturally involved if one thinks about a system/object.
- The question of whether something is viewed as an object or as a system cannot be answered by criteria that originate from the entity itself. Instead, the intentions of a person determine whether an entity will be viewed as a system or as an object. Accordingly, Bernard's (1865) statement that systems are in the heads of people, can be extended by adding that a system can only be found in the head of a person who looks at an entity with the intention of analysing it in a systemic way.
- We follow soft systems methodology (Checkland and Scholes 1990) in the suggestion that the methodology of systemic inquiry can itself be looked at as the subject of systemic inquiry.

2.3 Introducing Closure

Many years ago, Teilhard de Chardin wrote the following: “First, in the multitude of things comprising the world, an examination of their degree of complexity enables us to distinguish and separate those which may be called ‘true natural units’, the ones that really matter, from the accidental pseudo-units, which are unimportant.

The atom, the molecule, the cell and the living being are true units because they are both formed and centred, whereas a drop of water, a heap of sand, the earth, the sun, the stars in general, whatever their multiplicity or elaborateness of their structure, seem to possess no organisation, no 'centricity'. However imposing their extent they are false units, aggregates arranged more or less in order of density. Secondly, the coefficient of complexity further enables us to establish, among the natural units which it has helped us to 'identify' and isolate, a system of classification that is no less natural and universal" (Teilhard de Chardin, 1969).

Teilhard de Chardin had an intuitive notion of why certain objects were formed and centred, and other objects did not have such qualities. Yet it remained difficult at that time to offer precise criteria indicating why and when units were formed and centred. The question of what defines unity can also be recognised in the work of other authors including for example the metabolic repair system, and closure to efficient causation (Rosen 1958), autopoiesis (Maturana and Varela 1973), the hypercycle (Eigen and Schuster 1979; Kauffman 1993), the strange loop (Hofstadter 1979), closure (Heylighen 1989a,b, 1990; Chandler and Van De Vijver 2000), quanta of evolution (Turchin 1995) and agency/autonomy (e.g. Ruiz-Mirazo and Moreno 2012; Moreno and Mossio 2015).

Of all these criteria, the concept of closure is viewed in this book as a connecting principle because it can be linked to many of the other concepts. This is the reason why closure has been given a fundamental position in the Operator Theory. In the following paragraphs the concept of closure is explained followed by a discussion of how it is applied in the current book.

2.3.1 An Intuitive, General Explanation of the Concept of Closure

One of the oldest visualisations of closure is perhaps the ancient symbol of the Ouroboros, the snake that swallows its own tail and by doing so creates a structure of which the beginning and end meet. Closure has gained increasing interest in recent years. The use of the concept of closure in the current book was originally inspired by the works of Goguen and Varela (1979) and Heylighen (1989a,b, 1990). Later an international workshop about closure resulted in a book edited by Chandler and Van De Vijver (2000). Since that time closure has become the subject of an increasing number of publications notably by the group of Moreno, e.g. Mossio and Moreno (2010a,b), Ruiz-Mirazo and Moreno (2012), Mossio et al. (2013), Moreno and Mossio (2015) and the group of Letelier, e.g. Soto-Andrade et al. (2011), Letelier et al. (2003), Luz Cárdenas et al. (2010), Letelier et al. (2011).

Closure can also be expressed in mathematical terms, where it relates, for example, to the situation in which a set is closed for the performance of an operation on its elements. As a case: the set of natural numbers (0, 1, 2, 3, …) is closed for addition, but is not closed for subtraction, because $2-5=-3$, which is not a natural number. Closure represents a special property of a system because the state space of a closed system has become invariant (i.e. it does not change) under the internal dynamics (e.g. Heylighen 1990; Chandler and Van De Vijver 2000).

In this book the term closure is predominantly used in relation to the closed state that results from the closing process. Closure thus refers to a topology. Closure as a topology creates an intimate link between form and functioning, because specific functionalities of the elements have become unified through the emergence of a closure.

2.3.2 The Utility of Using Closure When Analysing Complexity

Closure is a potentially very powerful concept when creating a hierarchy of complexity. The reason is that closure has the unique property of unifying all the elements involved into a single entity, either conceptually or materially. This property of closure allows one to identify amidst of all the chaos in the world a select group of elements that together can be viewed as a single countable unit.

2.4 Defining Closure as It Is Used in This Book

The concept of closure in this book is based on the Operator Theory. Before discussing closure in a more formal sense, an intuitive introduction is offered of the concept. For this purpose one can imagine a piece of rope that lies on the table. From this rope different figures can be made, but if a person takes one end of the rope in the left hand and the other end in the right hand, and the ends are pulled apart, the result is a stretched piece of rope (possibly with some small knots) (Fig. 2.1a). Things are different if before stretching the rope, the two ends would have been knotted together. If the knot has loose ends the pulling apart of the rope's ends will result in a short stretch of rope that has a loop of rope dangling from it (Fig. 2.1b). If the knot was very close to the ropes ends, it is no longer possible to grasp the ends of the rope, because the rope has become a close to perfect loop (Fig. 2.1c).

The presence of this loop is what here is called closure. When one takes a two-dimensional picture of the loop, the loop surrounds an area and closes that area off from the area outside the loop. Because the surface inside the loop is surrounded, or enclosed by the rope on its outer edges, the configuration of the rope is named closed, and the part of the rope that creates the loop will be referred to as having closure.

This idea of closure can be generalised to spaces with more than two dimensions. This can be done by imagining that instead of a rope, one would use a sheet of rubber. This sheet of rubber can then be stretched and folded in such a way that (part of it) creates a box, ball or other three- or multi-dimensional shape which surrounds a specific volume of empty space and closes it off from the space outside.

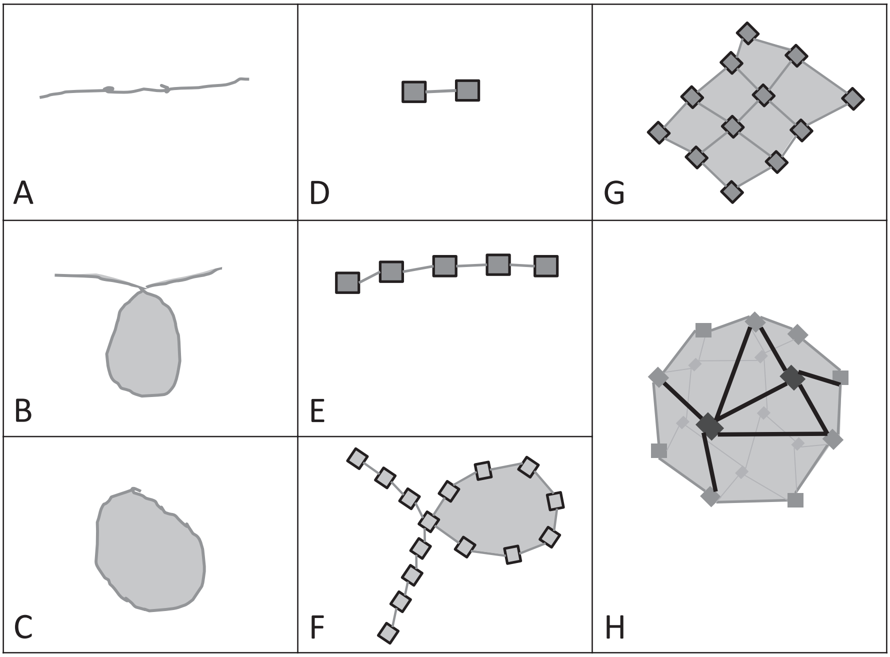

Fig. 2.1 Explaining closure in an intuitive way. For explanation of examples (**a**) to (**h**) see text of Sects. 2.4.1 to 2.5.1

2.4.1 *From a Rope to a Chain of Objects Connected by Relationships*

In the world, things do not generally consist of rope or rubber. This implies that for using the concept of closure in the world, the above examples will have to be generalised into a definition which covers closure in any physical object. For this purpose one can look at the world as if it consists of objects that are related in some way. If an object O_1 has a relationship with object O_2, the objects can be viewed as being linked by this relationship (Fig. 2.1d). And if an object O_1 links to object O_2, which links to object O_3 etc. to object O_n, the resulting chain of links can be viewed as a translation of the open configuration of a physical rope. Accordingly, any linear chain of links between object O_1 to O_n can be viewed as an open chain of interactions (Fig. 2.1e).

In the same way, one can also create a chain of objects with a loop in it. Let us imagine a chain of objects O_i with i ranging from 1 to 15. One now can imagine that the links O_5 to O_{12} form a loop, because there is a link from O_{12} back to O_5, while the links from O_1 to O_5, and those from O_{12} to O_{15} form chains that are open at one end, and that connect to the loop at the other end (Fig. 2.1f). In such a case, the part from O_5 to O_{12} has closure. As long as a chain of links does not have a loop, it is viewed as open. Because of this both a linear and a branching chain of objects are viewed as being open.

It is not so difficult to apply the object-based approach to the sheet of rubber that surrounds a volume. For this purpose one can imagine a number of objects that in a two dimensional way are connected to form a sheet (Fig. 2.1g). And this sheet of connected objects can be folded around an imaginary volume (Fig. 2.1h).

2.4.2 Closure Caused by One or More Moving Objects

In the above examples it was assumed that the objects had a fixed position in a chain or as part of a sheet. However, it is theoretically advantageous if closure can also be used in the case of one or more objects that move through space, and that follow a path that bends back onto itself (e.g. a planet going around the sun). The path that such an object follows can comply with the above definition of closure, because the path of the moving particle encloses a surface or space.

2.4.3 A Definition of Closure

Following the above preparations, a definition of closure can be deduced as follows:

> *Closure is the property that one or more entities behave and/or interact in such a way that the result can be viewed as surrounding a space in two (surface), three (volume) or more dimensions.*

2.5 Kinds of Closure

The above definition allows for a broad variety of closures. The Operator Theory does not use all such possibilities. Instead it focuses on a limited selection of specific kinds of closures: dealing only with what are called uniform closures of the functional and structural kind.

Uniform functional and structural closures are combined to create dual closure. Dual closure is used in the Operator Theory to identify next-level operators. The identification process starts with fundamental particles after which subsequent dual closures lead to the first kind of operator, and the next etc. In this way next kinds of operators are derived from previous ones in an iterative manner, resulting in the operator hierarchy.

When speaking about the iteration of dual closure, this may bring to one's mind the picture of a linear ranking of steps. However, the rules for dual closure are more intricate and can also lead to a branching pattern. The possibility of a branching pattern can be understood from an analogy with a ball. Using a ball as the starting point, there are not just one but two options for new closed configurations. One closed configuration is that of two balls that are attached like soap bubbles, with a shared contact surface, and one connected outer surface. Another configuration is that of a small ball inside a large ball. In analogy to the example of the ball, a ranking that is based on dual closures can lead to a linear ladder, but can also diverge into a branching pattern.

Whether or not dual closure leads to one or more different kinds of operators in the next step must be evaluated for every operator. This implies that if one investigates every step locally, which represents a localised, myopic point of view, there is no simple rule that predicts whether branching will occur, or what particular shape the next dual closure will have. When looked at the Operator Hierarchy this way there is no algorithm that allows one to predict the next dual closure. However, as discussed below, the Operator Theory focuses on regularities in the ranking for hypothesising that the overall ranking of all known kinds of operators has a higher order branching structure that may well be the result of an overarching algorithmic logic. The nature of this overall logic is the subject of ongoing research.

The following paragraphs explain further what is meant by the terms uniform closure, functional/structural closure and dual closure. After that, an explanation is offered how dual closures can be used to create the operator hierarchy.

2.5.1 Uniform Closure

As was said before, the Operator Theory only makes use of uniform closures. To explain what a uniform closure is, it is illustrative to first describe an example of non-uniform closure.

Imagine a set of three objects: a bicycle, an apple and a molecule. The relationships between these objects can be many, but one can for example imagine that the bicycle rides over the apple and crushes it, that the apple releases a molecule of a volatile apple-oil, and that this oil-molecule condenses onto the bicycle. In principle, the relationships from the bicycle, to the apple, to the molecule, to the bicycle can be viewed as representing a closure. In an example like this, however, both the objects and the relationships between the objects vary, and it is hard to identify an overall logic which binds the diverse elements together. One might therefore call a closure like this one, with different kinds of objects and different kinds of relationships non-uniform closure.

In contrast to a non-uniform closure, which can be based on objects and relationships of (very) different kinds, a uniform closure is based on objects which are all of the same kind, while the relationships between the objects are also all of the same kind. This statement begs the question: when are objects, respectively processes, of the same kind? The criteria for identifying the kinds of objects and processes that play a role in the Operator Theory are explained later on, for example in Sects. 2.5.4, 2.6.1 and 2.6.3.

2.5.2 *Functional Versus Structural Closure*

On top of only dealing with uniform closures, the Operator Theory also limits itself to functional and structural closures.

In a functional closure the objects are connected through links that can be viewed as unidirectional transformations. During a unidirectional transformation a first object alters the physical construction of a second object through a physical interaction, in such a way that the interaction either changes both objects, or only the second object. One can visualise successive unidirectional transformations as a chain of links represented by arrows from the first to the second object, the second to the third etc. Such a chain has functional closure when at some point the chain loops back onto itself and thus creates a closure of the process chain. This definition implies that a functional closure has a minimum size of two objects connected by two processes (arrows).

An example of a functional closure is given by a set of for example three catalytic molecules (M_1 to M_3) which transform substrate molecules to catalytic molecules that are part of the set. In this set, M_1 catalyses the production of M_2, M_2 that of M_3 and M_3 that of M_1. The relation between catalysts and molecules produced through catalysis forms the loop required for closure.

The other kind of closure that plays a role in the Operator Theory is the structural closure. Structural closure implies that a group of objects interact in a non-transformative way while their locations are confined by the formation of a closure. The closure can have two different forms: one form is that of a two dimensional surface that completely surrounds a volume, as in the case of a rubber ball where the rubber surrounds a volume of air. The other form is that of one or more moving objects whose paths create a closed shape. An example of the latter is an electron that is part of an atom. In this case, structural closure can be seen to occur in two ways. (1) When the electron returns to a point it was at before, thus closing a loop and (2) the set of its possible locations creates a sphere known as the electron shell, which completely surrounds the nucleus. Due to Pauli's exclusion principle, the electron shell has physical relevance, because the electron shells of two atoms experience increasing resistance when their electron orbits approach each other and overlap.

2.5.3 *Dual Closure*

Of all objects with closure, the Operator Theory deals selectively with objects that were formed through the combination of a functional and a structural closure, referred to as dual closure (addressed in singular).

There are two reasons for suggesting the use of dual closure. Firstly, and in analogy to the exclusion of non-uniform closures from the current approach, it is necessary to avoid that subsequent steps are based haphazardly on either functional or structural closure. After all, the goal here is not to end up with a ranking that is based on a mixture of rules, which could be viewed as representing a logically inconsistent ranking. Secondly, the aim is to create a ranking that selectively includes physical objects. On the one hand this goal immediately excludes entities defined by functional closure, because such entities are conceptual. On the other hand, if a ranking is based selectively on structural closures the ranking can include all sorts of enclosed objects, such as soap bubbles, hollow glass spheres, fatty acid vesicles and children holding each other's hands while dancing in a circle.

Through the use of dual closure the Operator Theory limits the options for any next kind of closure to a single next possibility, or to a few possibilities which are all based on the current dual closure.

2.5.4 The Use of Dual Closure in the Operator Hierarchy

The goal of the Operator Theory is to create a ranking that is also an ontogenesis for kinds of objects. For this purpose, the Operator Theory identifies a sequence of dual closures in such a way that every new dual closure is of a new kind, and defines a new kind of object. Every object of a kind that is included in this sequence is called an operator, and the sequence is called the Operator Hierarchy.

One of the goals of the Operator Theory is to create constancy in the naming of the kinds of operators. For this purpose the dual closure of a specific operator is used as an anchor for the naming of the kind of the operator, and sub-kinds.

A new operator is created through a new kind of dual closures that connect two or more operators of the current kind, thus creating the next operator in the hierarchy. The operators in the operator hierarchy refer to kinds of objects, not to specific objects. This means that any configuration of operators of the current kind which are linked through one or more dual closures of the new kind is an operator of the same new kind, i.e. any such object is placed in the same position in the operator hierarchy. The above generalisation can be understood more intuitively by comparing an operator with a brick structure and a dual closure with cement. In that case, the above principle says that the term brick structure is a general term that refers not to a specific structure, but to any structure made out of bricks that are held together with cement. Thus, any object made of the same kind of operator and the same kind of dual closure can be seen as being of the same operator kind. Accordingly, if atoms are the bricks and covalent bonds are the cement, both a diatomic structure, such as H_2 or O_2, is a molecule, the long chain of atoms in some fats or in lignin is a molecule, a sheet of connected atoms such as in graphene is a molecule, and a spherical structure of carbon atoms, a fullerene, is a molecule.

The sequence of all dual closures and associated kinds of operators follows the order in which they were first formed, and starts with cosmogenesis. The first kind of particles that currently are known to have been formed during the Big Bang are the particles that are studied by particle physics, the so-called fundamental particles that are described by the so-called standard model (Close 1983; Oerter 2006). In the

Operator Theory, all fundamental particles are seen as belonging to the same kind. The idea that they are of the same kind is not new. It is also the idea behind M-theory (Rickles 2014), which is more popularly known as string theory and which sees all fundamental particles as small strings. Whether fundamental particles have closures, and of what kind such closures are is currently unknown. For this reason the Operator Theory does not detail their closure, but accepts fundamental particles as the starting point for constructing a hierarchy of dual closures.

Generally speaking, the dual closure of the operator of the current level can be used to identify the dual closure of operator(s) of the next level. The single exception to this rule is the atom. In atoms the functional closure of the atom nucleus is based on hadrons, which represent operators. Meanwhile, the structural closure of the electron shell is based on one or more electrons, which represent fundamental particles instead of hadrons. Apparently, electrons have been the highest lower level possible for creating the structural closure of the electron shell, while at all higher levels it has been possible to create the next dual closure of the operators of the immediately preceding kind.

There is one final aspect of the use of dual closure that has to be explained, namely that the criterion of dual closure does not always lead to a single option for a next operator. In some cases two or more dual closures can be based on the current one. In such a case, the two new kinds of operator that are created out of the present one cause a branching of the ranking. And the new kinds of operator after the branching will be different, but will all reside at the next level in the hierarchy. As explained in the next chapter, the possibility that dual closure can lead to a branching of the ranking of the operators suggests that the ranking of all the kinds of operators follows higher-order logic.

2.6 Primary Structure and Secondary Structure of the Operator Hierarchy

All the transitions in the Operator Hierarchy are summarised in Table 2.1 and the steps in the table are explained in an accessible way in the accompanying text. For additional information on this topic the reader is referred to earlier publications on this subject (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2010a, pp. 37–55).

2.6.1 Primary Structure of the Operator Hierarchy

In Table 2.1, one finds all the kinds of operators, and the dual closure (functional and structural) on which they are based. The table also includes a distinction between the structural closure called interface and the functional closure called hypercycle. When separate, the interface and hypercycle do not represent an operator, because they only refer to a single closure, not a dual closure. Even though these uniform closures do not represent operators, the interfaces and pre-operator hypercyclic sets are included in Table 2.1 because they will play an important role in later analyses of the secondary structure of the ranking.

Even though the concept of dual closure in principle does not demand this, it is relevant to remark that dual closure can in practice frequently be identified because it involves an "advanced" property of the interacting operators. The advanced operators have a new property that adds something special to the repertoire of their interactions.

For example, of all the fundamental particles with mass, the quarks not only have mass, but are also known to emit and reabsorb (at high frequency) small force-carrying particles, called gluons. Gluons are relatively complex, because they convey a property that is known as "colour", which is conveyed as a combination of colour and anti-colour. This complex feature later became the basis for the functional closure of gluon exchange. Another example can be observed in neural networks. While all the cells of a multicellular touch their neighbouring cells and interact with them through plasma connections, a special new property of a subset of advanced cells was that they could connect cells that are not direct neighbours. This special property later formed the basis for the functional closure of the neural network.

The dual closures in Table 2.1 are explained in detail in the following sections.

The quarks are viewed as primitive objects, of which the kind of closure is unknown.

Quarks can interact through the exchange of other small fundamental particles, notably gluons. In this way quark–gluon plasma can be formed. When the quark–gluon plasma cooled, during the expansion of the universe, the gluon force-field became relatively strong, and the quark–gluon interactions condensed into small bundles of two or three quarks, a process called confinement. The exchange of gluons and the confinement represent a functional and structural closure, respectively, and thus a dual closure. The resulting kind of operator is called a hadron. Examples of hadrons are the proton and the neutron.

Protons and neutrons can emit and reabsorb small hadrons that consist of two quarks, and that are called pions. In the same way as quarks can exchange gluons, the hadrons can exchange pions, and in this way create an emission-absorption cycle. Bound protons and neutrons together are also viewed as a nucleus. The capturing of an electron shell creates a structural boundary around the nucleus. The combination of the nucleus and electron shell represents a new dual closure, and is called the atom.

The electron shell of an atom normally contains the same number of of electrons as there are protons in its nucleus. The electron shell of cell is built up in layers. The electrons orbit the nucleus and can be anywhere in their layer at any one time. Each layer can contain only a limited amount of electrons. For example: the innermost layer can only hold 2 electrons and the next two layers 8 each. A new layer is formed outside the previous one, but only when the previous layer is full. Apart from this layering, there is another important property, namely that electrons in the electron shell want to pair up with another electron. Atoms have a tendency to want to have

Table 2.1 The functional and structural closure that together allow a transition from an operator of a lower level kind to an operator of a higher level kind

Operator (or system kind)	Advanced property	Functional closure (transformation)	Structural closure (shape)	Operator	Operator code
Fundamental particle		First closure?		No	
Quark–gluon plasma		Gluon exchange between quarks		No	
Hadron	Quarks emit gluon carrying colour and anti-colour	Gluon exchange between quarks	Confinement (at low enough temperature)	Yes	1
Nucleus		Hadron-pion hypercycle		No	
Atom	Exchange of pion as two-quark object	Pion exchange between hadrons	Electron shell	Yes	10
Multi-atom (e.g. molecule, metal grid)	Orbit with an unpaired electron allowing for the formation of an orbit with paired electrons	Exchange of electron pairs between atoms	Coupled electron shell of shared pair of electrons	Yes	11
Auto-catalytic set		Catalytic hypercycle		No	
Cell (e.g. bacteria and archaea)	Molecules capable of catalysing molecular reactions	Set-wise autocatalysis	Cell membrane	Yes	100
Endosymbiont cell (e.g. protozoa, eukaryote cells)	Free living endosymbiotic cells	Obligate interaction between host cell and the endosymbiont	Cell membrane of the host cell	Yes	101
Multicellular (e.g. blue-green algae)	Developmental history with pluricellular stage	Plasma connections with neighbouring cells	Shared membrane after connection of the plasma	Yes	110
Endosymbiont multicellular (e.g. plants, algae, fungi)	Developmental history with pluricellular stage	Plasma connections with neighbouring cells	Shared membrane after connecting of the plasma	Yes	111
Self-referential system		Signal transduction hypercycle		No	
Hardwired memon	Cells or other "agents" that transfer signals to other cells or agents	Second order cycle of connections that alter the signal transduction of the receiver	Sensors	Yes	1000

the outer layer of their electron shell to be full. One way they can do that is by a pairwise sharing of some of the electrons in that outer layer with those of another atom. For example: the oxygen atom has 8 protons in its nucleus, and hence 8 electrons in its electron shell. The first layer therefor contains two electrons, while the second, and in this case outermost, layer contains 6 out of a possible 8. This means this layer is lacking 2 electrons. This lack can be solved by a pairwise sharing of two electrons in this layer with another oxygen atom. This sharing creates the more stable oxygen molecule, made up of two atoms. Electrons that are paired up in such a way can then orbit both atoms. The sharing of electrons in this way is known as a covalent bond which keeps the atoms close together. When the outer layer of an atom's electron shell is already full, it will not form covalent bonds with other atoms, and thus will never be part of a molecule. Such atoms are known as the noble gasses, which are therefore inert.

Molecules come in many varieties. Some of these can catalyse a reaction in which a substrate molecule is transformed into another molecule. A functional closure now emerges if, in a chain of catalytic reactions, the set of molecules created by the reactions is the same as the set of molecules that catalyse the reactions. Such a set of molecules is known as an autocatalytic set. At the same time, some products of the reactions of the catalytic cycle may form a vesicle that surrounds a volume of liquid in which the catalytic processes take place. When this happens, the catalytic cycle and the vesicle together represent a dual closure. The resulting system is the operator of the kind cell. Examples of this operator are the bacteria and the archaea.

The next operator is based on the interaction between cells. But now there are two topological possibilities for structural closure. A cell can interact with another cell that is attached to it, or with one that is inside it.

If a cell interacts with a cell that is attached to it, a dual closure emerges when the cells are linked through plasma connections across their membranes. Due to the plasma connections two or more cells interact in a transformative way, by the exchange of plasma, hereby creating a functional closure. And the plasma connections also create a connected outer surface, which represents a structural closure. The resulting kind of system is called the multicellular operator. Multicellularity of a group of cells thus implies that any cell is linked to at least one other cell in the group through plasma strands, and that every cell contributes to the functioning of one or more cells of the group in the context of maintenance of all the cells in the group as a multicellular organism. An example of this kind of operator is represented by the blue-green algae.

If a cell interacts with a cell inside it, the functional closure is realised through the obligatory dependency of the host cell on the metabolic activity of the endosymbionts, while the endosymbionts depend for their metabolism on the host cell. The structural closure involved is that of the membrane of the host cell, which acts as an interface for the endosymbionts with the outer world. The resulting kind of system is called the endosymbiont operator. Examples of this kind of operator are the protozoa.

By analogy with the multicellular operator, endosymbiont cells can, through a dual closure, create an endosymbiont multicellular operator, such as a plant, an alga and a mushroom.

From the endosymbiont multicellular operator a next dual closure can be reached in the following way. First, single cells connect through long extensions with other cells than their neighbours. These extensions connect multiple cells into groups that, through a first-order interaction cycle can act as information storage. A second order interaction cycle emerges when such first-order cyclic groups are connected to other such groups. The interactions between such groups represent a new kind of second-order functional closure. For a dual closure, the interacting groups of neural cells still need structural closure, which because of the demand of uniformity, has to be based on multicellular units. It is suggested for this reason that structural closure is represented by the groups of interacting neural cells that act as sensors. The combination of the hypercyclic interactions and the sensory interface is viewed as the hallmark of a new kind of operator, which has been named the memon. When analysed in this way, the tissues in which the neural system and interface are embedded, the ‘body’ that ‘surrounds’ the memon, becomes a kind of ‘vehicle’ for the memon. The memon as a neural entity depends strongly on feedback with its multicellular vehicle, because the interaction between both aspects is needed for maintenance of the entire construction. Because of this close interaction, the current text will generally use the concept of a memon as if it extends to the entire physical body in which the memon resides. For example, when a human is called a memon, this refers not just to the neural network, but includes the human body as the vehicle of the neural network. Accordingly, a memon will also be addressed as a neural network organism.

It is furthermore relevant to remark that in nature the first memons could only develop as a special kind of organs in multicellular organisms. For the Operator Hierarchy it is not necessary, however, that the agents that carry out the informational hypercycle are cells. In principle technical analogies of cells may perform processes that conceptually can be viewed as identical.

2.6.2 Secondary Structure of the Operator Hierarchy

By analogy with the way amino acids can be viewed as the primary structure, and the helix as the secondary structure of DNA, the Operator Theory also theorises that the ranking of the operators has a primary structure and a secondary structure.

The primary structure depends on the pairs of kinds of operators before and after a dual closure, e.g. hadron and atom, atom and molecule, molecule and cell, and cell and endosymbiont cell. (see Table 2.1). The secondary structure depends on patterns that recur in the kinds of transitions and the kinds of operators they connect. The following discussion of the secondary structure involves two steps. The first step focuses on transitions from one kind of operator to the next. The second step pays special attention to a number of closures that occurred before the first operator emerged.

Secondary Structure in the Ranking of All the Operators

Here it is hypothesised that the ranking of all the operators of different kinds has a secondary structure. This hypothesis has its roots in the observation that kinds of operators can be arranged in groups, each group being limited at the low end by a new kind of operator, and at the high end by an operator that consists of multiple attached operators. Inside such a group all the operators can be viewed as being constructed from the first operator of that group. For example, the atom is a new kind of operator at the lower end of the group, and the molecule is the operator that consists of attached atoms, and that forms the higher end of the group. One can also observe in Table 2.1 (third column, grey rows) that the first kind of operator in every group of the kind that is discussed here is preceded by a hypercyclic closure with interface.

The above groups of kinds of operators can include just a single operator kind, or can include two or more kinds of operators. Using Table 2.1 one can identify three examples of such groups:

1. The hadron, which represents the first and only operator kind in this group.
2. The atom and the molecule either are atoms or consist of atoms.
3. The cell, the multicellular, the endosymbiont cell, and the endosymbiont multicellular, which all are cells or consist of combinations of cells.

The above groups differ in the number of members, either a single or two or four, while the increase in the number of kinds of operators per group suggests an exponential pattern. The Operator Theory assumes that this exponential pattern is not an artefact of the way of analysing organisation, but that it can be viewed as representing a special kind of regularity in the organisation of nature. If this assumption is correct, there are two questions that need to be answered. The first is: What kind of regularity can describe a pattern like this? And the second is: What kind of mechanism can be found that can explain the emergence of such regularity? This section focuses on the first question. The second question is discussed in the thermodynamics chapter of this book.

One of the hypotheses of Operator Theory is that the exponential pattern in the number of kinds of operators per layer can be described by means of a simple abstract logic that is based on the following two rules. 1.The first rule is that the dual closure of any next kind of operator must always be of a new kind. Due to this rule, the dual closure of the current operator can never be of the same kind as that of the next operator. 2.The second hypothetical rule assumes that after a new kind of operator has formed, any next new kind of operator will have a dual closure that repeats, at a higher level, all the closure kinds at the preceding level.

The way these two rules work is demonstrated by the following example. If the current operator has dual closure of kind A, the first rule implies that the next operator must have dual closure of kind B (Fig. 2.2a). Given an operator of kind B, the second rule implies that the next new operator must have a dual closure that differs from B while repeating the kind of closure of A. Accordingly, the next new operator will have dual closure of the kind A(B), which coding indicates that a new kind of

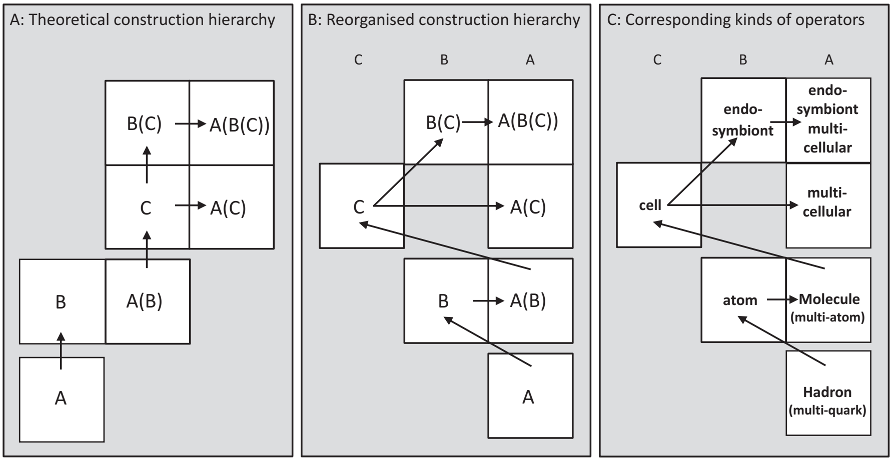

Fig. 2.2 Hypothetical algorithm for the second order ranking of the different kinds of operators. Part (**a**): The construction of increasingly complex kinds of operators based on a combination of the two hypothetical rules, the logic of which is explained in the text. Symbols *A*, *B* and *C* indicate different kinds of dual closure. Part (**b**): A reorganised representation of the ranking in part (**a**). Dual closures are sorted according to columns with a recurring similarity in the kinds of dual closure, indicated as *C*, *B* and *A* on *top* of a column. At the same time, every position in the hierarchy has its proper kind of dual closure. While the *arrows* seem to follow a different pattern in Fig. 2.2a than in 2.2b, this is an artefact of the new kind of ranking. Part (**c**): The mapping of real operators that correspond with the position in part (**b**)

dual closure A is formed that is based on the dual closure of operators of the kind B. Now all possible combinations based on B have been filled in, and because a next kind of operator must have a new kind of dual closure, this implies that the next new operator must be of kind C. For a proper understanding of the use of dual closure it is relevant that every next operator is based on the dual closure of the preciding operator, but that this does not necessarily imply that a next operator must always be constructed physically from operators of the preceding kind.

Using the two above rules, and based on the dual closure of the kind C, there are now three options for a next new kind of dual closure, namely A(C), B(C) and A(B(C)) (Fig. 2.2a). For example A(C) can be interpreted as a repetition of the A kind of dual closure based on operators of the kind C. Due to this logic, a ranking emerges that includes an exponential increase in the number of kinds of dual closure per layer, from 1 to 2 to 4 to 8 etc. While this hypothetical pair of rules describes a logic that can be matched with the pattern in the sequence of kinds of operators, it is still an open field of scientific inquiry to identify all the mechanistic explanations that create such patterns. Furthermore, based on the current understanding it cannot be excluded that in analogy to the system kind A(B(C)) producing a next series of systems, also A(C) can become the basis of next systems. At present, however, no known examples seem to exist of systems that fit into this hypothetical extension, due to which such an option is no more than a theoretical speculation.

In Fig. 2.2a the different kinds of operators are grouped based on dual closures of kind A, B or C. However, the way in which the kinds are organised does not offer a transparent overview of when a dual closure is new, and when it repeats a dual closure of a lower level operator. To improve on this situation, it was decided to rearrange the kinds of dual closure in a column-wise way (Fig. 2.2b). Since the repetition of the dual closure of kind A is always the last option before a new kind of dual closure is required, these closures are viewed as the most complex in the series, and are placed at the right side of the figure (Fig. 2.2b). In this way the "ladder" of dual closures of Fig. 2.2a is folded to highlight its column-wise regularity in Fig. 2.2b.

So far, the Fig. 2.2a, b depict relationships based on hypothetical rules. The link with real kinds of operators becomes apparent in Fig. 2.2c. It can be observed that every dual closure in the rightmost vertical column is of the kind A, and correspond with operators that consist of multiple attached objects of a uniform kind: the hadron, the molecule and the multicellular. In the hadron, the attached objects are quarks. In the molecule the attached objects are atoms. In the multicellular organisation the attached objects are either cells or endosymbiont cells. One column to the left, all the operators share a kind of dual closure that is associated with the character B. This dual closure involves an interface. In the atom the interface is the electron shell, and in the endosymbiont cell, the membrane of the host cell acts as an interface for the endosymbiont cell. Finally the cell has a new property (of kind C) which according to the Operator Theory is the capacity called the structural copying of information.

Apparently it is possible to relate the abstract rules and the ranking of specific operators. This suggests that nature fills in a regular pattern of positions in state space. These positions have also been referred to as slots in state space by Diedel Kornet (personal information).

Extending the Secondary Structure Below the Level of the Hadron

So far, the attention was focused on the ranking of the operators, of which the hadron is the least complex kind. A typical property of all the operators is their dual closure. However, the demand of dual closure excludes systems that lack the required pair of closures. To also include in the logic of the Operator Hierarchy the kinds of objects that preceded the hadrons, analyses must also include objects having a single closure dimension. A focus on such objects implies that structural and functional closures must be analysed independently of each other.

The early universe was filled with plasma of fundamental particles of different kinds. Some of these particles represented matter and others conveyed forces. The matter particles are either leptons (e.g. the electron) or quarks.

Here it is assumed that the particles in the standard model really represent the most fundamental level of organisation. Based on sting-theoretical models for quarks, every quark presumably exists as a self-interacting field that rolls up to a closed space, creating an interface between the quark and the world. The new kind of (single) closure that is introduced by quarks was for this reason named the interface closure.

Fundamental particles split off and reabsorb virtual particles, such as virtual photons, in a process called self-interaction. A special property of quarks is their capacity to emit and reabsorb force carrying particles of the kind gluon. The emission and reabsorption of a gluon can be viewed as a cyclic process. A cycle of cycles or second order cycle is formed when a quark splits off a gluon which is absorbed by a second quark, which splits off a gluon which then is absorbed again by the first quark. The Operator Theory refers to this second order cycle as a hypercycle. Any hypercyclic arrangement of gluons now represents the kind of (single) closure indicated as a hypercyclic closure. As the interactions in this cycle are of a transformative kind, they comply with the criteria for functional closure.

In the early universe all forms of hypercyclic closure between quarks were embedded in the quark–gluon plasma. When the universe expanded, however, the temperature dropped because the energy was dispersed over a larger space. And at lower temperatures the gluon field becomes relatively strong. If, at current temperature, one pulls two quarks apart, the gluon field stretches like anelastic band. When it snaps, the energy that is released is transformed into new quarks on either side of the breakpoint. As the result of this mechanism quarks always occur in bundles of two (mesons) or three (baryons). It is said that the gluon field confines the quarks. This confinement of quarks by the gluon field is viewed by the Operator Theory as a new kind of closure that repeats the interface kind of closure of the individual quarks (Fig. 2.3). Confinement can be viewed as a structural container around the functional process of gluon exchange, and complies for this reason with the criteria for structural closure.

By combining the hypercycle closure (functional) and the interface closure (structural), one obtains the first dual closure, which is typical for the hadrons (particles such as protons and neutrons). From this moment onwards one can continue with the logic of dual closure steps that was discussed above.

The above explorations have demonstrated that it is possible to identify two kinds of single closure that emerged during the first closure steps from quarks to hadrons. It is interesting to add this information to the scheme of Fig. 2.2.c. The result is a new scheme that starts with the first single closures and continues with the dual closures (Fig. 2.3).

At this place, the names of the closure dimensions on top of the columns in Fig. 2.3 are not discussed. This topic is detailed in Sect. 18.8 in relation to predictions of future operators.

Using Table 2.1 and Fig. 2.3 one can now define both the transitions between operator layers (BOL) and the transitions between operator kinds (BOK).

Examples of BOL transitions are all transitions in the operator hierarchy that introduce truly new kinds of closure. At the same time, every truly new kind of closure can also be viewed as opening up a new dimension. There are many examples of the early dimensions, notably the closure dimensions of the interface, the hypercycle, and the multi-particular state, For this reason, the strutures of these closure dimensions are relatively well understood (see the right columns in Fig. 2.3). The more recently a dimension has emerged, the fewer examples of it are known and the more difficult it becomes to perform secondary analyses and to identify the general factor that is typical for the dimension.

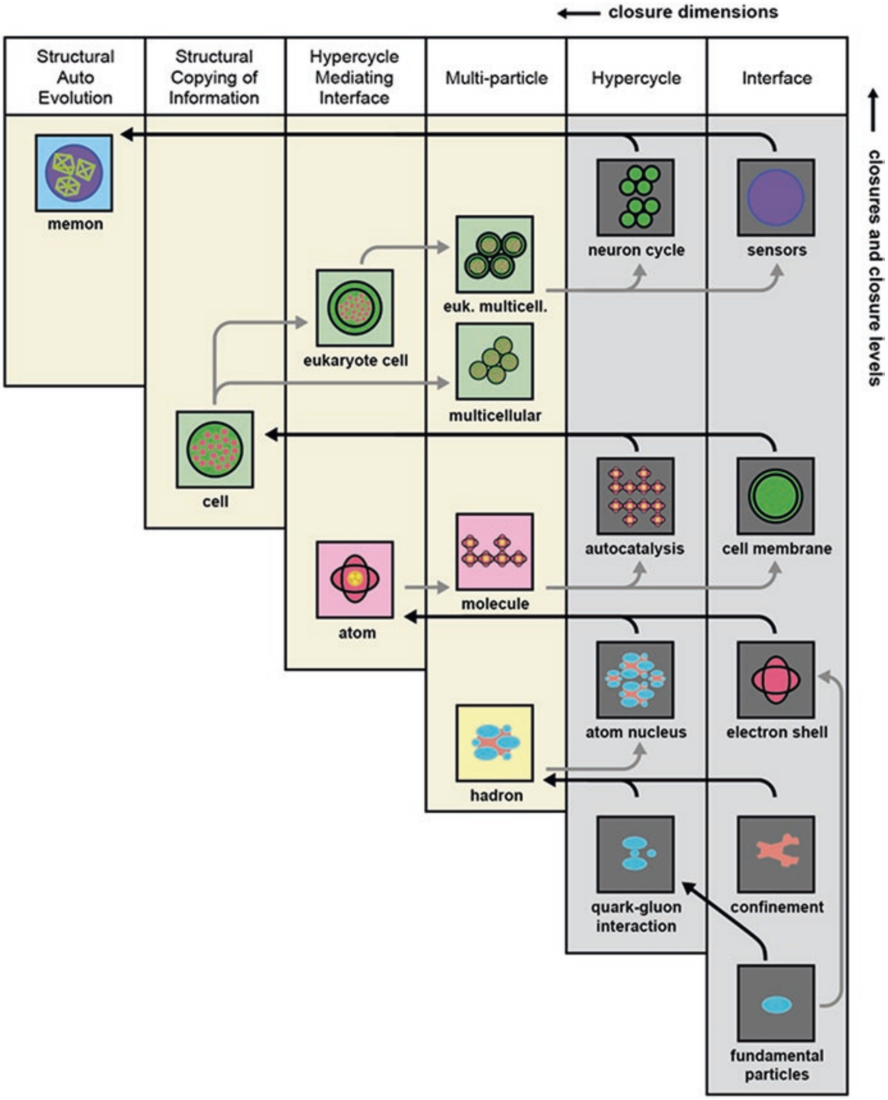

Fig. 2.3 The secondary structure of the Operator Hierarchy. *Grey columns*: conceptual stages that precede the formation of the first kind of operator at a next layer (pre-operator hypercyclic set, and interface). *Yellow columns*: operators and their closure dimensions. *Black arrows*: transitions towards the first operator at the next layer, named a BOL transition. *Grey arrows*: transitions towards new kinds of operators within a layer, named a BOK transition. Arrows that reach across two or more columns, do not indicate a gap in the logic, but are the result of the figure representing a two-dimensional projection of a higher dimensional logic. The corresponding author of this chapter has allowed A. Chatterjee to publish this figure in Chatterjee (2016, as figure 6), from which it is reproduced here with permission from Bentham

In the operator hierarchy the following six BOL transitions (a) and related closure dimensions (b) can be recognised:

1. First BOL transition: the fundamental particles.
   (a) Here scientists still speculate about the closures. A potential explanation based on string theory is the rolling up of a field-sheet to a long tube and the closure of the tube to a finite system; the torus of the closed string.
   (b) Fundamental particles are assumed to have the closure dimension of the interface, which is the first kind of closure of the operator hierarchy. Higher level pre-operator systems which also have the interface closure are: gluon confinement, pion exchange, the cell membrane, and the sensory interface.
2. Second BOL transition: The hypercyclic quark–gluon plasma.
   (a) This is represented by the second order process of quark–gluon exchange that connects two quark–gluon cycles in a hypercyclic arrangement.
   (b) The new closure dimension that is introduced is the hypercyclic closure, or hypercycle. At levels above the quark–gluon plasma this kind of closure can also be recognised in the pion exchange in the nucleus, in the set-wise autocatalysis and in the informational interactions between groups of neurons in neural networks. Set-wise autocatalysis differs from normal autocatalysis in the sense that in normal autocatalysis a catalyst changes a substrate into a copy of itself. Meanwhile, when set-wise autocatalysis occurs, the catalysts involved change substrate to other catalysts than themselves in such a way that if each of two catalysts would produce the other, they would together sustain the pair of them, and realise auto-catalysis of the set that is represented by the two atoms.
3. Third BOL transition: The hadron.
   (a) This is the first step in which dual closure occurs. The hadron combines the closures of the superstring hypercycle and the confinement of the quarks through gluon fields.
   (b) The new closure dimension that is introduced is that of the multi-particle. Examples of multi-particles at levels above that of the hadron are: the multi-atom (e.g. a molecule or a lump of metal), the multicellular organisms, and the endosymbiont multicellular organism.
4. Fourth BOL transition: The atom.
   (a) The dual closure is based on the nuclear hypercycle and the electron shell.
   (b) The new closure dimension that is introduced is that of the hypercycle mediating interface. Based on only two examples it is deduced that what is important about this dimension is the spatial separation of a hypercycle and a mediating interface. This interfacing is repeated in the endosymbiont unicellular.
5. Fifth BOL transition: The cell.
   (a) The dual closure is based on the catalytic hypercycle and the cell membrane.

   (b) The new closure dimension that is introduced is that of the structural copying of information. Here the deduction of the closure dimension is difficult, because there is only a single example that can be used. It can, for example, be assumed that the new property the cell allows for is the structural copying of information in the cell. Another option could be to focus on unit-wise information processing.

6. Sixth BOL transition: The memon.
   (a) The dual closure is based on the neural hypercycle and the sensory interface.
   (b) The new closure dimension involved is deduced to be structural autocopying of information.

It must be noted that the closures of BOL transitions (interface, hypercycle and the combination of interface and hypercycle) are dealt with separately when analysing them from the point of view of system organisation. At the same time, however, these two closures have generally occurred simultaneously during the natural processes that formed an operator.

2.6.3 Systems That Include Two or More Operators: The Interaction Systems

Because it has dual closure, an operator always represents a countable, structural and functional whole, and a physical unity. For this reason, an operator can function in the Operator Theory as the basic building-block for analysing systems that consist of multiple operators (Fig. 2.4). Any such system (the system concept has been

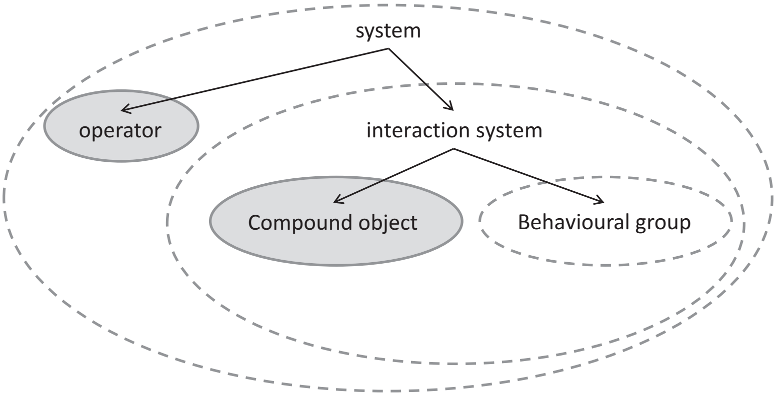

Fig. 2.4 The fundamental ontology that the Operator Theory uses for the identification of major kinds of organisation. *Dashed circles* indicate conceptual entities. *Circles with grey shading* indicate physical units

discussed in Sect. 2.3) that includes two or more operators, and that does not represent an operator itself, will be viewed as an interaction system (Jagers op Akkerhuis 2008, 2014). Examples of interaction systems are a population, a family, a society, a car and a football.

The concept of an interaction system is defined by invoking set theory. An interaction system and its material objects are associated with a set which has at least two entities, named the elements of the set. The number of members of an interaction system decreases when two or more objects integrate physically. Inside the large set of all possible interaction systems one can create subsets of various kinds. The reason why many subsets can be created is that one can imagine many criteria and combinations of criteria for deciding which objects will belong to a specific subset. Criteria can be spatial, e.g. all organisms in a specific area. Or criteria can be based on taxonomy, e.g. all the organisms of the same species (which concept requires further criteria to be specified). Criteria can also be based on social interactions, e.g. the wolves that cooperate as a pack, the mating of organisms, and the giving birth to offspring. Many more selections can be envisioned. Of all the possibilities, two special subsets are the compound objects and behavioural groups.

Compound objects are highlighted because, just like operators, they represent countable physical/material unities. In the literature about knowledge representation compound objects have also been referred to as chunks, in the interpretation of continuous pieces of matter (e.g. Bennett et al. 2000; Davis 1993, and Needham 2002). A compound object consists of operators and/or compound objects which are more closely attached to each other than to their environment, and which can be displaced as a structural unity relative to the environment (as explained in Jagers op Akkerhuis 2008), e.g. a stone, a drop of water in oil, a piece of cloth, and a car. The term compound object is never used for an operator. Complex compound objects can be formed through the lumping of less complex compound objects. A special kind of compound objects is formed through the attachment of single celled organisms, leading for example to the slug of the cellular slime mould *Dictyostelium discoideum* and the eight-cell stage of the human embryo. The reason why these are called compound objects, and not organisms, is that the cells lack the plasma connections required for dual closure. Instead of as an organism, the Operator Theory views the slug and the early embryo as *pluricellular compound objects*.

Another special kind of interaction system is the behavioural group, which is defined as a consciously made selection of organisms which are not attached and which can be viewed as being united through some kind of interactive relationship. Making a conscious choice about which organisms belong to the group and which do not is necessary for three reasons. Firstly, as long as one talks about individually dwelling organisms, the interactions do not define a form of material unity. For this reason the criterion of attachment cannot be used to identify the members of a group. Secondly, the number of possible relationships that an organism can have with entities in its environment is almost infinite. This implies that one has to consciously select specific relationships between specific organisms when defining a behavioural group. For example, in a specific environment wolves will eat mice, dig burrows, mark their territory and have many more interactions, but only the social interactions with some other wolves are selected for the identification of the wolves that are a member of a specific pack. Thirdly, if one uses a functional criterion without additional spatial criteria, this can have marked consequences. For example if one uses the potential to mate as the criterion for membership of the global population of a species, this leads to problems in the cases of ring species where all neighbouring individuals can mate, but where at the geographical edges of the population at least two groups of individuals exist that can not mate or can not produce fertile offspring.

A property of interaction systems is that the objects involved can be grouped according to fully or partially overlapping subsets. For example horses can be grouped according to herds or populations, as wild horses or as riding horses. Additionally, and in a (partially) overlapping way, the individuals of different species that are present in a specific area can be grouped according to more inclusive criteria, which results for example in communities and ecosystems. Another example of overlapping criteria is the participation of a person in different groups, such as a company, a family, a debating club and a tennis club. The subsets of people in the different clubs are not the same, and may show some overlap, for example when a single person participates in two or more groups. At the same time, there may also be several colleagues of this person, who participate in the same tennis club, but not in the other groupings.

2.7 Discussion

2.7.1 General Remarks

The Operator Hierarchy is based on the concept of dual closure. Dual closure adds a novel perspective to existing system theories about objects and hierarchical levels of organisation, e.g. by Von Bertalanffy (1950), Simon (1962), Turchin (1977), Koestler (1978), Miller (1978), Salthe (1985), Heylighen (1990), Alvarez de Lorenzana (1993) and others. It is important to realise that the functional and structural aspects of dual closure are always the results of underlying dynamics, and that for this reason the Operator Theory is not just an administrative classification of closure kinds but also a mechanistic ranking.

An object that has (dual) closure, can of course lose its closure. This happens for example when the construction and/or dynamics are reduced to below a specific minimum for the kind of closure, for example, an atom that is heated stops to be an atom when it loses the last electron shell, or a multicellular organism can be starved and loose its capacity of maintenance, and finally die and disintegrate.

While closure is an absolute necessity for activities/processes such as metabolism and maintenance, this logic cannot automatically be inversed, as the example of crows illustrates. Most crows are black birds, but this does not imply that most black birds are crows. By analogy, while the metabolism of organisms requires functional closure of the processes involved, this does not imply that a system that is not metabolically active does not have closure. An example is a frozen bacterium. As long as all the molecules are preserved that are involved in the autocatalytic closure, and as long as the membrane of the bacteriumis intact, dual closure is present, and the frozen bacterium can be thawed and become fully functional again. This is the reason why such a frozen state has been called viable lifelessness. A consequence of this unidirectional logical relationship is that closure can be viewed as being more fundamental than metabolism because one needs closure for metabolism, while as the example of the frozen bacterium illustrates- metabolism is not necessary for closure.

At the end of this paragraph special attention is asked for the non-classical naming that the Operator Theory introduces. The classical indication that the bacteria and the archaea represent prokaryotes can be viewed as an approach that has worked towards increasingly small objects. For a long time it had been impossible to observe structures much smaller than those of eukaryote cells. And when the first microscopes finally offered a view of the bacterial world, these were classified as prokaryotes, the organisms that do not have a nucleus in their cells. As the Operator Hierarchy reasons from the bottom up, a system that resides at a higher level in the operator hierarchy, such as a eukaryotic cell, cannot serve as a reference as long as it still has to be constructed. A similar logic applies to the single celled organisms that belong to the group that classically is named Protozoa. In the Operator Hierarchy the Protozoa are classified as endosymbiont cells. They are called endosymbiont cells (and the cells living inside them are called endosymbionts) because the Operator Theory emphasises the dual closure that is associated with the endosymbiont cell(s) that live inside an endosymbiont cell. When identifying the next step after the cell, the Operator Theory emphasises the presence of the endosymbionts instead of the presence of the karyos. The operator theory focuses on the presence of the endosymbiont, because the structure of the karyos is not present in all stages of the life cycle of all eukaryotic species. During cell division, the karyos of many species temporarily dissolves. The advantage of focusing on the presence of endosymbionts is that the endosymbionts in a cell can never disappear, because they are part of an obligatory interaction with the host cell. Finally, the Operator Theory does not in all cases use the word animal. The reason is that the concept of the animal in the classical naming system can equally well be applied to single celled protozoa such as Paramecium as to multicellular animals. To prevent confusion when using the concept of the animal in this way, and in accordance with the dual closure of the neural network, the Operator Theory makes use of a new concept, the memon for the class of neural network organisms. Accordingly, all memons are animals, but not every animal is a memon.

2.7.2 Using the Operator Hierarchy for Defining the Organism Concept

As has been indicated in the general introduction the debate about how the organism concept can be defined does not seem to have ended yet. About the role of the organism concept in the life sciences Nicholson (2014) says the following: “Although organisms were deemed to have been explained away, in retrospect a more accurate assessment is that they were merely abstracted away. In molecular biology, the complexity of the organism's organization was taken for granted as the experimental focus shifted towards the detailed mapping and analysis of metabolic pathways, signalling cascades, and the regulation of gene expression. Likewise, in the Modern Synthesis view of evolution, the agency and autonomy of organisms were not even recognised as theoretical problems but were simply presupposed in the models of population genetics and behavioural ecology."

One of the things that may have blocked the road towards consensus about a definition of the organism concept is that classical approaches start with inventories of different kinds of things that are viewed as organisms such as bacteria, viruses, archaea, protozoa, sponges, corals, plants, algae, fungi, lichens and animals. After this inventory has been made, criteria are sought that can cover all these cases. What is special about such an approach is that the examples were selected more or less haphazardly, based on a loose collection of criteria that roughly coincide with properties that organisms generally have. For example, one may have used reproduction as a criterion for considering an example as an organism. Indeed most of the examples may potentially reproduce. But the technical aspect that is relevant for a definition is, whether or not reproduction offers a necessary and sufficient criterion? Can it be confirmed that every example that is considered as an organism can always reproduce (think of a single animal that is locked up in a cage)? And is it always true that if a system cannot reproduce it can never be an organism (think of a sterilised cat, or a mule)? Similarly, one could focus on the use of metabolism as a criterion for whether or not an entity represents an organism. Now it is easy to on the one hand indicate many things that have some form of metabolism but are not organism-like, such as a flame, or a compost heap. And on the other hand, there exist things that are organisms but that do not have metabolism, such as a frozen bacterium. The use of reproduction and metabolism as criteria also leads to questions about what *exactly* is meant with these concepts. If one uses for example reproduction or metabolism as criteria for deciding whether or not an object belongs to the set of organisms the next challenge becomes to define precisely what the criterion means, because any variation in the interpretation of reproduction or metabolism will lead to a different selection of objects.

The Operator Theory now offers an alternative approach to defining the organism concept that contributes to resolving the above discussions. As was discussed in Jagers op Akkerhuis (2010b, 2012a, b), the Operator Theory offers a basis for defining the organism concept in two steps. The hierarchy of all the operators serves as the first step. And as the second step, one can choose to -by definition- only select as organisms those kinds of operators that are at least as complex as the cell. If one uses these two steps, the organism concept is defined from the bottom up. Based on this approach, only the following kinds of operators represent organisms: the cell (conventionally called a prokaryote), the (prokaryote) multicellular (e.g. blue-green algae), the endosymbiont cell (conventionally called a eukaryotic cell, but named differently by the Operator Theory because of the relevance of the endosymbiont), the endosymbiont multicellular (e.g. a plant) and the organism with neural network (the so-called memon, see Fig. 2.3).

As has been discussed for example in Jagers op Akkerhuis (2010b, 2012a,b) using the Operator Hierarchy as a basis for defining the organisms, offers clarity about which entities are organisms and which are not. The operator-based criteria allow one to identify the operators that are organisms amidst of the many other systems which are not an operator, such as the slug of a slime mould, symbiotic relationships, herds, colonies and bee hives. As a consequence of this approach some of the classical examples of organisms, such as viruses, sponges and lichens have to be set aside. And the classical criteria such as reproduction, metabolism and response to stimuli will have to be reconsidered. When using the new definition, only specific kinds of complex operators are viewed as organisms, and the essential property of an organism has become its level-dependent kind of dual closure. This novel approach implies a major re-conceptualisation of the discussions in this field.

The operator theory also clarifies the difference between cell theory, and organismal theory (e.g. as discussed by Nicholson 2010; Nicholson and Gawne 2014, 2015). It does so by emphasising that a cell has dual closure, and that combinations of cells can also have dual closure. Both a cell, and a group of cells that have dual closure, are viewed as an organism. This indicates that in a single cell the criteria for dual closure and the criteria for being an organism are in full overlap. In systems that consist of multiple cells, however, the cells have one particular kind of dual closure and the multicellular organisation has another particular kind of dual closure. And for the Operator Theory it is the highest level closure that determines the kind of the operator.

2.7.3 Relating Classical Hierarchy and the Operator Theory

Those readers who are familiar with classical approaches in natural hierarchy, in biological/ecological hierarchy and in ecotoxicology, will have noticed that such approaches generally make use of a linear ranking, a "ladder", in which lower level elements are subordinate in some way to higher level elements. However, the Operator Theory offers tools to allow that more complex hierarchies can be thought of, as is also suggested by the following citation of Bickhard and Campbell (2003) stating that: "The important point … is that ratchets of stability of emergent forms can form ladders and more complex hierarchies—hierarchies of some kinds of new organizations and emergents that make possible other kinds of organizations and emergents. Such hierarchies impose an organization on the potentialities of progressive emergence: these hierarchies constitute intrinsic constraints on the possible courses of cosmology and evolution".

As a supplementation of classical approaches that are based on a linear ranking, the Operator Theory proposes a conceptual framework for synchronic observations that works along three complementary lines, called dimensions (see Fig. 2.5). These dimensions are:

1. The Operator Hierarchy (the ranking of all the kinds of operators along the upward dimension).

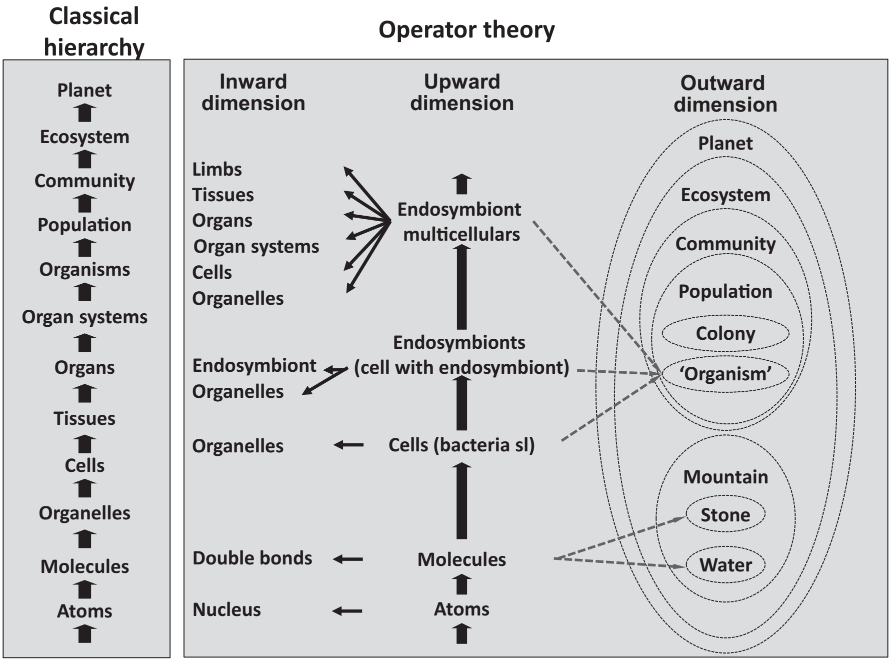

Fig. 2.5 A comparison of the classical hierarchy (*left*) based on a single dimension, and the new approach of the Operator Theory (*right*) based on three dimensions. *Dashed circles* indicate abstract conceptual groupings of increasing inclusiveness. Classical approach: levels are connected by *thick solid arrows*. Operator Theory: *Thick solid arrows* indicate the levels of the Operator Hierarchy along the upward dimension. *Thin solid arrows* indicate parts along the inward dimension. *Dashed arrows* indicate the belonging of specific operators to one or more conceptual groupings along the outward dimension

2. The organisation inside any individual operator (the inward dimension).
3. The organisation of systems that consist of interacting operators (the outward dimension).

In fact, it can be suggested that changes over time can potentially be viewed as adding a fourth dimension, representing the diachronic perspective.

The motivation for this multi-dimensional viewpoint is that each of the dimensions leads to a specific kind of ranking that is based on a specific kind of entities and ranking rules. For example the upward dimension selectively ranks operators of increasingly complex kinds, e.g. atom, molecule and cell. while the ranking rule is based on dual closures. The inward dimension focuses on an operator, and studies the material construction inside (e.g. organs and tissues in a multicellular organism). The outward dimension ranks increasingly general subsets of objects.

While the upward dimension has a stringent ranking that is based on (dual) closures, the ranking of objects along the inward and outward dimension is sensitive to the perspective that is used during the ranking process. For rankings along the inward or outward dimension, one can choose different viewpoints that can be grouped according to the following major properties: Displacement, Information, Construction, and Energy. These different perspectives for analysing organisation have been indicated with the acronym DICE (Jagers op Akkerhuis 2008). The following paragraph offers some examples of how DICE can be applied to the inward and outward dimension.

When studying organisation along the inward dimension the following example demonstrates how DICE can be applied, Displacement can for example focus on the way that vessels and veins transport blood, and the way blood cells transport oxygen. Informational relationships can focus for example on how ribosomes read the DNA and how messenger RNA is produced, and transcribed resulting in amino acids. Construction relationships can focus on organs in multicellular organisms, and on the way organs are constructed. And energy relationships can focus on the uptake of food, and the different ways energy from the food is used in the body.

Along the outward dimension one can identify many different groupings of objects. Examples of such groupings at increasing levels of abstraction are for example a population, a community and an ecosystem. Or one can identify grouping of increasing size, such as hamlets, towns, cities and mega-cities. Many different perspectives can be used for the ranking of objects into groups. While such perspectives can be ranked using the dimensions of the DICE approach, also other approaches can be selected. Using DICE one can for example analyse an ecosystem as follows. When using feeding relationships, which belong in part to the construction dimension of DICE, and in part to the energy dimension, one can rank organisms into food chains. And when using displacement interactions, one can create a classification in which objects are transported either by wind or water, or by insects, birds, humans etc. And constructional relationships can be used to develop a tree of interactions in which for example bacteria grow on the skin of a mosquito larva, which lives in the water in the heart of a bromeliad, which grows on a tree, which grows in the soil.

The Operator Theory thus recognises three dimensions, upward, outward and inward, and suggests that classifications along the inward and outward dimension always depend on the perspective that is chosen, while these perspectives can be grouped according to DICE. In this way, the Operator Hierarchy helps creating awareness about the use of distinct kinds of concepts and ranking rules.

As an example of how the viewpoint of the Operator Theory contributes to classical approaches, one can look at the following example of a classical ranking: cells, organs, organisms, populations. In this ranking the objects are of different kinds: cells are either operators or parts of an organism, organs are always parts of an operator, the organism represents a conceptual class that may include various bacteria, protozoa, plants and animals, and a population represents a conceptual grouping of selected objects. Besides that ranking of the Operator Theory organises the different kinds of objects, it also organises the broad range of ranking rules. For example, the step from cell-to-organ, and from organ-to-organism will generally take place in an inverse direction, namely from a small multicellular organism with specialised cells, to a large multicellular organism that has multicellular organs. Finally, the step from organism-to-population represents the conceptual step from a single element to a conceptual grouping of consciously chosen elements.

The three dimensions discussed so far are all synchronic dimensions, in the sense that they focus on the organisation of system at a specific moment. Of course one can also focus on the change or development of systems over time, using a diachronic perspective. The diachronic approach could be viewed as a new dimension that analyses things in a forward way. Along such a forward dimension one can analyse how organisms during their development change from one developmental stage to the other, and how interactions in ecosystems change, e.g. during succession.

2.7.4 Relationships with the Major Evolutionary Transitions Theory

The Operator Hierarchy is closely related to the Major Evolutionary Transitions theory that has been proposed by Szathmáry and Maynard Smith (1995). The Operator Theory adds new insights concerning the use of structural criteria and the classification of kinds of transitions. Firstly, all the major evolutionary transitions are based on the select use of three functional criteria (cooperation, competition reduction and reproduction as part of a larger unit), while the Operator Theory elaborates this viewpoint by suggesting the use of structural criteria in addition to functional criteria. Secondly, in the Major Evolutionary Transitions theory, all transitions that fit the criteria are viewed indiscriminately as major evolutionary transitions. The Operator Theory adds to this that the transitions that are referred to as major transitions differ in their kinds, and can be named according to these kinds. The Operator Theory also indicates that some transitions are relatively more complex than others, such as the BOL transitions, and that transitions may on the one hand lead to new kinds of operators (atoms, molecules, cells etc.), while on the other hand they may lead to new kinds of systems consisting of interacting operators (populations, societies). Studying the relationships between the Operator Theory and the Major Evolutionary Transition theory is relevant, because the relationships offer a basis for discussing how the use of structural criteria can contribute to the creation of hierarchical rankings. The relationships between the two approaches are discussed in detail in Chaps. 8–11.

2.7.5 Using the Operator Theory for an Ontology of Artefacts

From an ontological perspective, the Operator Theory primarily offers a hierarchy of kinds of operators. When looking at ontology from a causal perspective, this hierarchy itself represents a causal ranking of what came first and what came later. For example the formation of a cell necessarily must precede the formation of a multicellular. In the same way, one can create a conceptual classification of different operators or interaction systems that could form because a specific operator was involved. For example, a farm can be viewed as a physical system that intelligent beings have constructed to produce agricultural products in an efficient way. This implies that one first needs intelligent beings, before there can be a farm. Basically, if one uses the logic of the Operator Theory, a farm classifies as an interaction system.

One can even be more precise in the classification of a farm as a system kind. In Jagers op Akkerhuis (2008) it was explained that the Operator Theory classifies interaction-systems after the highest-level operator that is involved in the system. And the most complex entities involved in a farm-system are either the farm animals or the owner of the farm as a human animal. Animals with a neural network are also called memons by the Operator Theory. This implies that a farm classifies as a memic interaction system. A scheme which organises all the causal relationships that lead to different kinds of operators and different kinds of interaction systems is offered in Fig. 2.6). As it is designed by humans, who classify as memons, a farm is viewed as a memic system of memic origin (Fig. 6.2: an interaction system of the kind M -> M). Likewise, if humans modify a bacterium by means of genetic engineering, such a bacterium would classify as an operator of the kind cell, of memic origin. Similarly, a hammer would classify as a molecular interaction system of memic origin (in Fig. 2.6: M -> mA) because the hammer is constructed by memons, and because the most complex operators involved in the construction of the hammer are of a molecular kind (the wooden/metal handle and the metal head). Likewise, a lignin molecule would classify as a molecular operator of multicellular origin (in Fig. 2.6: mC -> mA).

2.7.6 Summarising What Is New About the Operator Theory

The Operator Theory has been the inspiration for some marked innovations in the thinking about objects and hierarchy.

Firstly, the Operator Hierarchy suggests that, because it involves a mixture of kinds of objects and kinds of ranking criteria, it may be profitable to re-conceptualise the classical perception of (ecological) hierarchy that is based on a single dimension. For unravelling which different kinds of objects and relationships are involved, a new approach is suggested which uses three independent dimensions (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2008):

1. An upward dimension for all the vertical transitions from quarks to neural network organisms.
2. An inward dimension for the levels of organisation inside an operator, such as organelles in a unicellular organism, and organs in a multicellular organism.
3. An outward dimension for analysing complexity in interaction systems, such as populations.

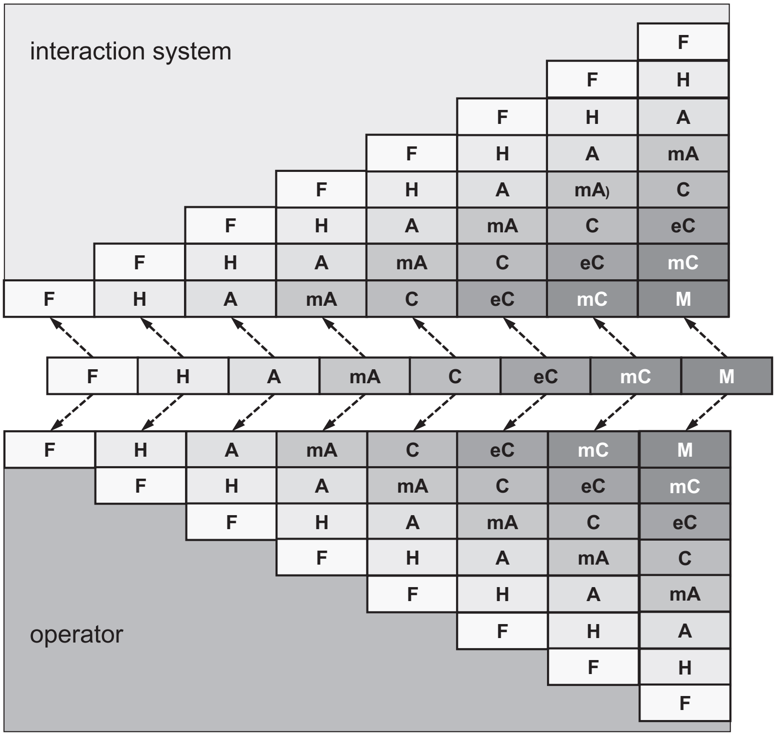

Fig. 2.6 A causal classification of operators of different kinds, and the operators and interaction-systems they produce. *Middle*: a ranking of operators of increasingly complex kinds. *Top*: a rankig of interaction systems produced by operators. *Bottom*: a ranking of operators produced by operators. *Abbreviations*: *F* fundamental particles, *H* hadrons, *A* Atoms, *mA* multi-atoms ("molecules"), *C* cells ("prokaryotes"), *eC* endosymbiont cells ("eukaryotes"), *mC* multicellulars, *M* memons (neural network organisms)

Secondly, dual closure is brought forward as a general criterion for the hierarchical ranking of systems which are all of the same major kind, namely that of the operator. The use of dual closure also offers a basis for a stringent ranking of levels of (a specific kind of) complexity.

Thirdly, in close relation with the three dimensions for hierarchy, the Operator Theory allows a stringent top-level classification of major system kinds as operators and interaction systems (Jagers op Akkerhuis 2008).

Fourthly, the logic of the Operator Theory can be used to name developmental histories and life cycles after the highest kind of organisation included. Consequently, a bromeliad, a mushroom, and kelp classify as being part of a multicellular life cycle, while a tiger is part of the neural network life cycle.

Fifthly, the operator hierarchy offers a novel solution to the long standing challenge of defining the organism concept: only operators from the level of the cell and up are viewed as an organism.

2.7.7 Current Status and Future Goals

The Operator Theory is linked to the hypothesis that topological rules have guided nature through a long and specific sequence of increasingly complex operators. It seems as if there is a law in nature that limits the complexity of the operators to specific steps, that are guided by dual closure. In order to assess the validity of the Operator Theory one can examine the validity of the assumptions that underlay every individual transition. As another test, one can examine the secondary structure of the Operator Hierarchy, or the predictions that result from extrapolating the Operator Theory towards future kinds of operators.

While the Operator Hierarchy can be viewed as an interesting innovation that offers a foundation for exciting theoretic developments, it cannot be excluded that other ways may be found for creating a structured overview of the foundations of the organisation of the universe. How can one choose between such alternatives? To answer this question one can use Ockham's razor for comparing the effectiveness of the criteria of alternative hypotheses.

Focusing on the Operator Theory from an axiomatic perspective, there is an interesting observation to be made. Primarily, the goal of the Operator Theory is to develop a reasoning that results in an ontology that can be constructed from the bottom up. Such ontology should start at the beginning of the universe, and should describe all kinds of systems that formed over time, until finally organisms with brains emerged who can reason and construct a conceptual framework for analysing complexity in nature. A particularly challenging task that remains is to express the logic of the Operator Hierarchy mathematically, in all its detail, for example by using a framework based on topology. Such a framework should enable the prediction of every single step in the Operator Hierarchy and should also produce the hierarchy's secondary structure. The use of mathematics may assist in resolving some aspects of the theory which currently are not understood in full depth, such as the following aspects that still demand technical and conceptual elaboration: 1. The question of what exactly are the multicellular units that form the basis of the step from the multicellular to the memon, 2. The question of whether the hypothetical existence of unicellular organisms with multicellular endosymbionts is relevant for the structure of the Operator Hierarchy, or falls in the class of 'endosymbionts of any kind' which applies for example to the endo-endosymbiont cells, 3. In the electron shell of an atom the electrons originate from two levels below the level of the atom, which is in constrast with all other steps in the Operator Hierarchy where the next dual closure involves the operators of the preceding level, and 4. The challenge of predicting accuratley any next kind of operator above the level of the hardwired memon. While these four points still pose challenges, the Operator Theory in its current status can be viewed as providing a framework that suggests many novel pathways for theoretical and practical research in system science.

Interestingly, while in the universe all entities were formed in a long sequence of processes, it is not possible to use that same sequence as an axiomatic basis for thinking about the universe. The reason is that most of the time there was no one present to identify and classify the things that happened or were formed such that they could be used for the construction of an axiomatic ontology. Things just happened. A possible solution to this problem is to accept that—with hindsight—one acts as if one can observe and classify the developments in the universe as through the eyes of an independent observer. And it is the role of this independent observer to construct a representation that suits the criteria of an axiomatic ontology, which finally includes sentient beings, and their thoughts about the world. As soon as a specific ontology includes sentient beings, and their thoughts, the ontology can use these entities as a basis for including conceptual representations. Subsequently, every object in the world can be described by means of a conceptual representation. From this point onwards, an intelligent being can work with a conceptual axiomatic ontology, representing his/her thoughts about what happened in the universe before the existence of intelligent beings capable of thinking about the universe. In fact, when talking about the Operator Hierarchy its structure represents the latter viewpoint. The Operator Hierarchy offers a conceptual representation that describes and ranks all the construction steps in the universe that are based on (dual)closure, and the kinds of objects that are produced by such steps.

The Operator Theory is a new theory. The earliest conceptual drawings of it stem from 1994. Since that time, the approach has offered a starting point for many challenging theoretical developments, such as those discussed in the following chapters of this book.

References

Alvarez de Lorenzana JM (1993) The constructive universe and the evolutionary systems framework. In: Salthe SN (ed) Development and evolution: complexity and change in biology. MIT Press, Cambridge, Appendix pp 291–308

Bennett B et al (2000) Describing rigid body motions in a qualitative theory of spatial regions. Proceedings of the Seventeenth National Conference on Artificial Intelligence and Twelfth Conference on Innovative Applications of Artificial Intelligence, AAAI Press, pp 503–509

Bernard C (1865) Introduction à l'étude de la médecine expérimentale. Paris. http://classiques.uqac.ca/classiques/bernard_claude/intro_etude_medecine_exp/intro_medecine_exper.pdf

Bickhard M, Campbell D (2003) Variations in variation and selection: the ubiquity of the variation-and-selective-retention ratchet in emergent organizational complexity. Found Sci 8(3):215–282. doi:10.1023/A:1025046917589

Chandler JLR, Van De Vijver G (2000) Workshop on closure: emergent organizations and their dynamics, Gent, Belgium, 3–5 May 1999: preface. Ann N Y Acad Sci 901:ix–xi

Chatterjee A (2016) Energy, Entropy and Complexity: Thermodynamic and information-theoretic perspectives on ageing. In: M. Kyriazis (2016) Challenging Ageing: The anti-senescence effects of Hormesis, Environmental Enrichment, and Information Exposure. Bentham

Checkland P, Scholes J (1990) Soft systems methodology in action. Wiley, Chichester, West Sussex, England

Close F (1983) The cosmic onion: quarks and the nature of the universe. Heinemann Educational, London

Davis E (1993) The kinematics of cutting solid objects. Ann Math Artif Intell 9:253–305

Eigen M, Schuster P (1979) The hypercycle: a priciple of natural self-organization. Springer, New York

Feibleman JK (1954) Theory of integrative levels. Br J Philos Sci 5:59–66

Goguen J, Varela F (1979) Systems and distinctions, duality and complementarity. Int J Gen Syst 5:31–43

Heylighen F (1989a) Self-organization, emergence and the architecture of complexity. In: Proceedings of the 1st European conference on system science. AFCET, Paris, pp 23–32

Heylighen F (1989b) Causality as distinction conservation: a theory of predictability, reversibility and time order. Cybern Syst 20:361–384

Heylighen F (1990) Relational closure: a mathematical concept for distinction-making and complexity analysis. In: Trappl R (ed) Cybernetics and systems '90. World Science, Singapore, pp 335–342

Hofstadter D (1979) Gödel, Escher, Bach: an eternal golden braid. Basic Books, New York.

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organization of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2010a) The operator hierarchy, a chain of closures linking matter life and artificial intelligence. Ph.D. Thesis, Radboud University, Nijmegen

Jagers op Akkerhuis GAJM (2010b) Towards a hierarchical definition of life, the organism, and death. Found Sci 15:245–262

Jagers op Akkerhuis GAJM (2012a) The pursuit of complexity: the utility of biodiversity from an evolutionary perspective. KNNV Publisher, Ziest, The Netherlands.

Jagers op Akkerhuis GAJM (2012b) The role of logic and insight in the search for a definition of life. J Biomol Struct Dyn 29:619–620

Jagers op Akkerhuis GAJM (2014) General laws and centripetal science. Eur Rev 22:113–144

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego-bricks of nature: evolutionary transitions from fermions to neural networks. World Futures J Gen Evol 53:329–345

Jaros GG, Cloete A (1987) Biomatrix, the web of life. World Futures 23:203–224

Kauffman SA (1993) The origins of order: self-organization and selection in evolution. Oxford University Press, New York

Koestler A (1967) The gost in the machine. Hutchinson & Co, London

Koestler A (1978) Janus, a summing up. Hutchinson & Co. Ltd., London

Letelier JC, Marín G, Mpodozis J (2003) Autopoietic and (M, R) systems. J Theor Biol 222(2):261–272. doi:10.1016/S0022-5193(03)00034-1

Letelier J-C, Luz Cárdenas M, Cornish-Bowden A (2011) From L'Homme machine to metabolic closure: steps towards understanding life. J Theor Biol 286:100–113

Luz Cárdenas M, Letelier J-C, Gutierrez C, Cornish-Bowden A, Soto-Andrade J (2010) Closure to efficient causation, computability and artificial life. J Theor Biol 263(1):79–92. doi:10.1016/j.jtbi.2009.11.010

Maturana HR, Varela FJ (1973) Autopoiesis and cognition: the realization of the living. Reidel Publishing Company, Dordrecht, Holland

Miller JGM (1978) Living systems. McGraw-Hill, New York

Moreno A, Mossio M (2015) Biological autonomy: a philosophical and theoretical enquiry. Springer, Dordrecht, The Netherlands

Mossio M, Moreno A (2010a) Organisational closure in biological organisms. Hist Philos Life Sci 32(2–3):269–288

Mossio M, Moreno A (2010b) Organisational closure in biological organisms. Hist Philos Life Sci 32:269–288, The Concept of Organism: Historical, Philosophical, Scientific Perspectives

Mossio M, Bich L, Moreno A (2013) Emergence, closure and inter-level causation in biological systems. Erkenntnisse 78:153–178

Needham P (2002) Chemical substances and intensive properties. In: Earley J Sr (ed.) Chemical explanation: characteristics, development, autonomy. Annals of the New York Academy of Sciences 988:99–113

Nicholson DJ (2010) Biological atomism and cell theory. Stud Hist Philos Biol Biomed Sci 4:202–211

Nicholson DJ (2014) The return of the organism as a fundamental explanatory concept in biology. Philos Compass 9(5):347–359

Nicholson DJ, Gawne R (2014) Rethinking Woodger's legacy in the philosophy of biology. J Hist Biol 47:243–292

Nicholson DJ, Gawne R (2015) Neither logical empiricism nor vitalism, but organicism: what the philosophy of biology was. Hist Philos Life Sci 4:345–381

Oerter R (2006) The theory of almost everything: the standard model, the unsung triumph of modern physics. Penguin Group, New York, USA.

Rickles D (2014) A brief history of string theory: from dual models to M-theory. Springer Science & Business Media

Rosen R (1958) A relational theory of biological systems. Bull Math Biophys 20:245–260

Ruiz-Mirazo K, Moreno A (2012) Autonomy in evolution: from minimal to complex life. Synthese 185(1):21–52. doi:10.1007/s11229-011-9874-z

Salthe S (1985) Evolving hierarchical systems: their structure and representation. Columbia University Press, New York

Simon HA (1962) The architecture of complexity. Proc Am Soc Philos Sci 106:467–482

Soto-Andrade J, Jaramillo S, Gutierrez C, Letelier J-C (2011) Ouroboros avatar: a mathematical exploration of self-reference and metabolic closure european conference in artificial life, ECAL 2011, Paris

Szathmáry E, Maynard Smith J (1995) The major evolutionary transitions. Nature 374:227–232. doi:10.1038/374227a0

Teilhard de Chardin P (1969) The future of man. Collins, London. (Original: Editions du Seuil V, Paris, 1946)

Turchin, VE (1977) The phenomenon of science, a cybernetic approach to human evolution. Colombia University Press, New York.

Turchin V (1995) A dialogue on metasystem transitions. In: Heylighen F, Joslyn C, Turchin V (eds) The quantum of evolution: toward a theory of metasystem transitions. Gordon and Breach Science Publishers, New York (special issue of ‘World Futures: The Journal of General Evolution, vol 45, 1995)

von Bertalanffy L (1950) An outline of general system theory. Br J Philos Sci 1:134–165

Whitehead AN, Russell B (1910) Principia mathematica 1, 1st edn. Cambridge University Press, Cambridge, JFM 41.0083.02

Whitehead AN, Russell B (1912) Principia mathematica 2, 1st edn. Cambridge University Press, Cambridge, JFM 43.0093.03

Whitehead AN, Russell B (1913) Principia mathematica 3, 1st edn. Cambridge University Press, Cambridge, JFM 44.0068.01

Woodger JH (1937) The axiomatic method in biology. Cambridge University Press, Cambridge

Woodger JH (1939) The technique of theory construction. University of Chicago Press, Chicago

Chapter 3
Reflections on the Operator Theory

Henk Barendregt

Abstract This review offers a short summary of the Operator Theory, or O-theory, including the notion of closure consisting of some circular processes. Based on closure, the Operator Theory distinguishes a limited number of levels in the organization of nature: fundamental particles, hadrons, atoms, molecules, and cells, cells with endosymbionts, multicellular organisms, and organisms with neural networks. The Operator Hierarchy can be viewed as a meta-evolution theory, the higher levels of which describe ordinary Darwinian evolution. Special attention is paid to objects that are produced by higher level objects in the Hierarchy but are playing a role at a lower level. For example living organisms have added complex biological molecules to the collection of lifeless molecules.

3.1 Introduction

The *O-theory* (operator theory) of Gerard Jagers op Akkerhuis is an approach that offers a uniform view of important phenomena in the universe since the Big Bang. It considers a short hierarchy of objects: (1) elementary particles, (2) hadrons, (3) atoms, (4) molecules, (5) cells, (6) endosymbiont cells, (7) multicellular organisms, and (8) organisms with brains. At each level of this hierarchy the objects create a wealth of interactions, which leads to a proliferation of evolving objects, and the formation of new kinds of objects. In this way O-theory is a (generalized) description of evolution. Also a uniform mechanism is described by which a level is transformed into the next level. Once objects of a higher level are present, the evolution of objects of the previous level continues and may even be enriched by objects that are produced by the higher level objects.

For example, at level 4 atoms form molecules by covalent binding. The resulting world of interactions is the field of chemistry, focusing not only on the molecules

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_3

(M) but also on the reactions. Among the possible reactions there are circular ones, possibly involving catalyzers. Such circular reactions are depicted as (*):

$$(*)\mathrm{M}_1 \to \mathrm{M}_2 \to \dots\dots \to \mathrm{M}_n = \mathrm{M}_1.$$

Such a circular chain of transformations may soon terminate, for example when the needed catalyzers are taken away due to environmental change. If, however, there is a protecting topological container for the process (*) and its catalyzers, then it becomes easier to maintain the circular reaction. If moreover the topological container is supported by the products of the circular reaction, then the interaction between the circular process and container is maintained. This mechanism is called a *closure*. Chemical closure brings forth a transition to the next level of complexity: the living cell.

We have in general the following.

1. The objects of a given level are being transformed, forming objects of varied complexity.
2. Some of these interactions from a circular transformation, like (*).
3. This circular reaction may be protected by a container, functioning on the basis of the given reaction and mediating the relationship between the contained processes and the world.

The combination of the circular reaction and its supported and supporting container is called an *operator*, and signifies the next level in the hierarchy. And then the story repeats.

Notice that (2) and (3) point at two different kinds of circles: one in time and one in space (albeit a 3D circle, i.e., a sphere). O-theory is an appropriate name, because the letter O indicates both kinds of circles.

Based on closures the O-theory allows the distinction of a limited number of levels in the organization in nature.

Level 1: fundamental particles.

Level 2: from elementary particles to hadron. The formation of hadrons (protons and neutrons) from elementary particles can be seen this way. In the very early universe after the Big Bang temperature is too high to have stable interactions between elementary particles. All particles interact more or less randomly and a “soup” results, consisting of elementary particles including quarks and electrons. After sufficient expansion and hence cooling down of the universe interactions between quarks are stabilized because the exchange of gluons creates a field around triplets of quarks, and these become confined into bundles called hadrons, of which protons and neutrons are examples. This is the first development.

Level 3: from hadrons to atoms. There are stable coalitions among hadrons. Actually these are only stable in the sense of (*): disappearing and appearing again. This way a nucleus of an atom is created. The nuclei are subject to change if more hadrons become part of the coalition. When the environmental temperature becomes low enough the electrons may form protecting containers. In this way the atoms are formed. While all the atom nuclei that are lower or equal in weight compared to the iron atom form in an exothermic way, all atom nuclei that are heavier require energy to be formed. For example a Zn (zinc) nucleus cannot form in the sun. Such atoms have to be formed by a supernova explosion.

Level 4: from atoms to molecules. The formation of molecules starts with the atoms that bind through covalent bonding. Such bonding typically involves the exchange of a pair of electrons in a shared electron shell. The atoms transform each other all the time, and the electron shell causes a shared container.

Level 5: From molecules to the cell. This level was already discussed: the complex pre-biological evolution starts, producing at some point the cell as a circular process contained in the cell membrane.

Level 6 plus: From here onwards levels continue to form, from the cell to multicellular organisms. The cells make coalitions and form multicellular compounds. First there was the simple unicellular organism (archaea). Then there is in parallel the formation of blue-green algae (prokaryotes) and of endosymbiont cells (like the eukaryotic cell). The endosymbiont cell is already the product of a closure and may be called level 7. Based on endosymbionts complex multicellular organisms could evolve. If in this evolution a circular event between cells takes place that at the same time produces a common container for all the cells involved, then a multicellular organism is evolved. In the O-theory the hallmark for multicellularity is the connection of cells through plasma connections.

The evolution of organisms at level 5 and above is the ordinary Darwinian evolution.

3.2 Other Aspects of the O-Theory

An important aspect of O-theory is that some objects x of a given level can often only be produced by starting at the next level, forming a higher-order object in which x plays a role, and then isolating x. For example, a complex biochemical molecule (like a vitamin) most probably will not arise in the evolution of atoms and molecules. It needs the more complex next level, the living cell, to be evolved first. But then of course it can be considered on the previous level, after isolation. Similarly an organ like a liver appears only on the level of living organisms, after which it can be taken out. I would suggest to refer to objects like mentioned x as “higher-order.” They exist at level, say, n, but can be evolved only by going to level $n+1$. Another interesting higher-order object is ammonia NH_3. The energy needing transition $3H_2 + N_2 \rightarrow 2NH_3$ happens in nature in some bacteria or in an industrial process (Haber–Bosch process). Only through this process, requiring a pressure of 400 atm, seven billion people can be fed via fertilizers. Put differently: without the availability of the higher-order molecule NH_3 there would not be so many people on earth.

Jagers op Akkerhuis constructed the O-theoretic view in order to explain that the usual way of looking at complex matter (via the classical sequence: atom, molecule, organelle, cell, mammal, population, ecosystem) is unsatisfactory for several reasons. Firstly, the notion of higher-order object is missing. Secondly, the objects included in the rankings are of different kinds, such as operators (atom, molecule, and cell), higher-order objects (organelles, organs), aggregations (planet), and abstract sets (population, ecosystem). Thirdly, the ranking rules between steps are not of the same kind. For example the way molecules are formed from atoms, is different from how organs are formed in organisms.

An important lesson to be taken from O-theory is to duly emphasize that there has not been evolution at just one level, namely the Darwinian evolution at the level of the organisms, but there is also “evolution” that leads to the emergence of new kinds of operators: such as from atoms to the cell and from the cell, via the endosymbiont cells, to the multicellular organism.

As discussed in detail in the Chaps. 4 and 6, O-theory provides a uniform description of different kinds of (Darwinian) evolution. And it emphasizes that all these kinds of (Darwinian) evolution are worthwhile topics for research. The common mechanism of Darwinian evolution that is discussed in next chapters is as follows. Some of the evolved objects will not take part in the next closure and some may take part, which can be identified as a pattern of selection. This fundamental pattern in an (exponentially) evolving tree of possibilities is what can be recognized as evolution, according to Darwin, when speaking about organisms. In O-theory the explanatory power of this mechanism is used for the identification of previous level, and future level patterns of Darwinian evolution.

In summary, O-theory provides a differentiated view on evolution, by distinguishing Darwinian evolution at several levels and by classifying in a natural hierarchy all the kinds of objects that play an important role in patterns of evolution.

Chapter 4
Darwinian Evolution: Process or Pattern?

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> *"The purpose … is to express Darwin's theory of evolution as a deductive system in which a few fundamental principles of the theory are used as axioms from which the remainder of the principles of the theory can be deductively derived. The value of such a deductive system (or axiomatization) is that it provides a technique for discovering new phenomena which are too remote from observation or too unintuitive to ever be discovered with the unaided intuition…"*
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> (Williams 1970).

Abstract Darwinian evolution is a central tenet in biology. Conventionally, the definition of Darwinian evolution is linked to a population-based process that can be measured by focusing on changes in DNA/allele frequencies. However, in some publications it has been suggested that selection represents a state, not a process. If this is true any definition of Darwinian evolution that includes selection no longer can represent a process, because the ontological kind of selection is that of a state. There are other publications that also suggest that the concept of evolution needs a rethink, for example to deal with epigenetics, niche construction and horizontal DNA transfer. As a basis for contributing to both demands for re-conceptualisation, we will explore in this chapter whether or not the definition of the concept of Darwinian evolution can be defined in a stringent individual/object-based way, in terms of individual parents and their individual offspring, instead of in terms of populations of parents and offspring. The reason why we focus on an individual/object-based approach is that this offers a basis for explicit descriptions of the objects involved and of the kinds of relationships between the objects, while a com-

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DOI 10.1007/978-3-319-43802-3_4

bination of these aspects offers a basis for decisions about which kind of over-all graph-pattern can be used for defining the concept of Darwinian evolution. Taking advantage of such possibilities, we suggest a graph-pattern for Darwinian evolution at the smallest scale. This smallest graph-pattern also offers a foundation for future scaling and extension. In the context of evolution, where everything seems prone to change, the pattern of Darwinian evolution at the smallest scale would also offer an unchanging core conceptualisation. We emphasise that the population viewpoint and the use of DNA/allele frequencies offer a solid and practical basis for calculations. In addition to this, we see theoretical reasons for the application of object-based graph-patterns as a means to solve ambiguities about how Darwinian evolution can be defined conceptually.

4.1 Introduction

Evolution stems from the Latin root *volvere*, meaning to roll. The extension *evolvere* means unrolling or forward rolling. Due to the generality of this Latin root many phenomena, both physical and biological, can be viewed as representing such a *sensu lato* interpretation of evolution. And in relation to the broad Latin origin, the literature offers a broad range of very different definitions of evolution (Table 4.1). As a subset of this broad range, this book will focus on the more narrowly defined concept of Darwinian evolution, which kind of evolution is generally associated with the production of descendants, and the preferential survival in next generations of descendants with specific (inherited) properties compared to descendants with other properties.

Probably because the Latin word *evolvere* is a verb, it is common practice to view evolution and every aspect of it as a process. Recently, however, several authors have questioned this viewpoint. In particular, the criticism has been directed at the concept of selection. For example, Ghiselin (1969, p 29, 51) has remarked that selection no more acts on organisms than erosion acts on a hillside. The suggestion is that by analogy with erosion as a state which results from the activity of water and wind, selection is a state which results from differences in mortality. Also Endler (1986) views selection as the outcome of heritable biological differences in the survival capacity of organisms. And Matthen and Ariew (2002, p 79) write that ‘natural selection is a mathematical aggregate of individual events. This seems to imply that it is not a causally connected process’. Recently, Corning and Szathmáry (2015) indicate that ‘…selection is really an umbrella concept that refers to whatever functionally-significant factors … are responsible in a given context for causing differential survival and reproduction’. and continue with saying that ‘Hence, we believe one cannot (technically) speak of a ‘mechanism’ or fix on a particular ‘selection pressure’ in explaining the workings of natural selection, these are only shorthand expressions’. The comments of all these authors strongly suggest that it may be valuable to analyse the variables involved in Darwinian evolution. If one or more variables, e.g., selection or variation, really do not represent processes, this raises questions about whether or not their integration into a definition of Darwinian

Table 4.1 An overview of different definitions of evolution. The table also indicates the major mechanisms that are involved and the kinds of entities

Scientific discipline	Description of evolution	Mechanism	Entities
Latin	Evolvere means unrolling, e.g., of a scroll.	Unrolling	General. May assume a predetermined path, or unrolling into the adjacent future
Natural philosophy	Evolution is the opposite of dissolution. 'Such, then, are the universal laws of that re-distribution of matter and motion everywhere going on—a re-distribution which results in Evolution so long as the aggregation of matter and dispersion of motion predominate; but which results in Dissolution where there is a predominant aggregation of motion and dispersion of matter'. (Spencer 1854 in Spencer 1891) (Note: the concept of motion currently would be interpreted as free energy or heat).	Aggregating (of matter), dispersing (of motion)	Physical objects, organisms
Biology	Evolution is 'the theory of descent with modification through variation and natural selection' (Darwin 6th ed. 1876, p 404).	Descending, varying, selecting	Species, organisms, cultural habits
Biology	Biological (or organic) evolution is change in the properties of populations of organisms or groups of such populations, over the course of generations. The development, or ontogeny, of an individual organism is not considered evolution: individual organisms do not evolve. The changes in populations that are considered evolutionary are those that are 'heritable' via the genetic material from one generation to the next (Futuyma 1998).	Changing of properties over generations	Populations, groups of populations
Cosmology	Evolution is any process of formation, growth and change with time, including an accumulation of historical information; in its broadest sense, both developmental and generative change (Chaisson 2001).	Developing and generation	Not specified
Natural philosophy, physics, biology	Variation-and-selective-retention ratchet. Hierarchies of new kinds of organisation and emergents constitute intrinsic constraints on the possible courses of cosmology and evolution (Bickhard and Campbell 2003).	Ratcheting	Kinds of organisation. Emergents

(continued)

Table 4.1 (continued)

Scientific discipline	Description of evolution	Mechanism	Entities
Technology	Technology evolves by constructing new devices and methods from ones that previously exist and in turn offering these as building blocks for the construction of further new devices and elements (Brian Arthur and Polak 2006).	Combining	Devices, methods
Philosophy	Evolution is the historical occurrence of *change* (Losos 2013).	Not specified	Not specified

evolution can actually be viewed as a process. To answer such questions, a thorough inspection of the definition of Darwinian evolution is required.

In addition to the nature of selection, three other aspects of Darwinian evolution are the subject of continuing debate in the literature. The first aspect that is discussed in the literature is the idea that evolutionary theory needs a rethink that allows the theory to be extended in such a way that it can account for recent biological insights about epigenetics, niche construction theory and horizontal DNA transfer (e.g., Odling-Smee et al. 2003; Pigliucci 2007; Pigliucci and Müller 2010; Depew and Weber 2013; Laland et al. 2014). A recent study by Laland et al. (2015) offers a detailed sketch of the extended evolutionary synthesis and how it is composed of processes that generate novel variation, processes that bias selection, processes that modify the frequency of heritable variation, and how such processes in combination lead to phenotypic evolution.

The second aspect of discussion aims at the generalisation of Darwinism to applications outside biology (e.g., Hodgson and Knudsen 2006; Aldrich et al. 2008). Generalised forms of Darwinism are in use in several fields outside biology, for example in evolutionary epistemology (Campbell 1960; Popper 1972), in generalised Darwinism (Hodgson and Knudsen 2006; Aldrich et al. 2008; Stoelhorst 2005, 2008; Levit et al. 2011), and in the contexts of universal Darwinism (Dawkins 1983) and universal selection theory (Cziko 1995). And in technology generalisations exist in the form of genetic algorithms and evolution in virtual ecosystems, for example Tierra (Ray 1995, 2009) or Polyworld (Yaeger 1994). In economy discussions involve evolution in business ecosystems (e.g., Metcalfe 1998; Beinhocker 2006; Stoelhorst 2010; Piepenbrock 2009). In sociology the central concepts are memes, learning and culture (Dawkins 1976; Blackmore 1999; Mesoudi 2010; Buskes 2013, 2015; Hannon and Lewens 2013).

The third aspect deals with evolutionary changes that are of a different kind than the changes based on genes. Classically, Darwinian evolution has focused on small genetic changes over generations, such as are caused by mutations, recombination, transposons and the epigenetic methylation of base pairs. In addition, however, when thinking about a general approach to Darwinian evolution, it must also be considered whether such an approach has to include the possibility of dealing with larger steps, such as may occur when several objects integrate and in interaction form a new, complex object. After all, without the possibility of including such steps, traditional Darwinian evolution cannot offer a complete explanation for the emergence of increasingly complex kinds of organisms in the tree of life. The analysis of large steps in biology dates back to Stebbins (1969), Bonner (1974) and Buss (1987, p 171). Maynard Smith and Szathmáry (1995) and Szathmáry (2015) started naming such larger steps "major evolutionary transitions".

In a context that extends outside biology and includes physical systems, early ideas about large steps in evolution have also been suggested by Teilhard de Chardin (1969). A more recent example of a general viewpoint that makes use of larger steps is that of Bickhard and Campbell (2003) who discuss a variation-and-selective retention ratchet for explaining how interactions between lower level objects, both physical and biological, produce higher level objects. The idea of combinations of objects can also be found in the work of Brian Arthur (Brian Arthur and Polak 2006; Brian Arthur 2009) who describes structural transitions in the context of technology in terms of combinatorial evolution. Finally, the Operator Hierarchy of Jagers op Akkerhuis (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2001, 2008, 2010) uses a combination of structural and functional criteria for defining in a stringent way the kinds of organisation of objects both before they integrate to a higher level organisation, and after the event. As was explained in Chap. 2, the criteria the Operator Theory uses for the identification of such transitions are general, in the sense that they can be applied both inside and outside biology.

The above indicates that there are four entangled issues that invite to a critical appraisal of the concept of Darwinian evolution: selection, extension, generalisation and transitions. The goal of this book is to contribute in different ways to the identification of resolutions to the questions that are raised in the discussions about these topics. While working towards this goal we will make use of an object-based approach. The reason why we choose an object-based approach is that this fits in with the axiomatic approach that was discussed in the general introduction (Chap. 1), and offers the advantage of allowing for precise reasoning that can be constructed from the bottom up, while being amenable to specification, scaling and extension. Before Darwinian evolution can be expressed in an object-based manner, there must be clarity about what can be viewed as Darwinian evolution.

4.1.1 Darwinian Evolution

The concept of Darwinian evolution refers to Darwin's ideas about evolution. Darwin summarised his ideas about the concept of evolution as: '…descent with modification through variation and natural selection' (Darwin 1876, p 313). And Darwin (1859, pp 80–81) defined natural selection as: 'This preservation of favourable variations and the rejection of injurious variations, I call natural selection'. When phrased this way, Darwin includes into evolution a selection concept which does not simply refer to the mortality of individual organisms. Instead, selection is introduced as a measure for differentiality in the sense that some individuals, the ones with favourable variations, perform better because their fit with the environment is better, while the organisms with injurious variations apparently do not fit very well.

To supplement the evolution theory of Darwin with new insights about genes an integrative approach was developed around 1940 that was called the Modern Synthesis (Huxley 1942). Just as Darwin's work, the Modern Synthesis has a concept of evolution that is defined in differential terms, and that focuses on how relatively successful organisms in a population are in transferring their genes to next generation organisms. To be able to handle in their calculations the effects of the random recombination of genes in sexual populations, and the probabilistic effects of environmental impacts on survival, modellers have focused on population averages, such as DNA/allele fractions. In response to calculations that made use of averages also the definition of Darwinian evolution was expressed in terms of changes in fractions of genes or alleles or other properties in populations over generations (Mayr and Provine 1998).

The above inventory indicates that there are two popular ways of defining Darwiniane volution: on the one hand Darwin's approach based on criteria, and on the other hand the modern synthesis focusing on changes in the fractions of DNA/alleles. In addition, the different interpretations of evolution mix with the four discussion topics that already were listed above, namely selection, the extension of Darwinian evolution, the generalisation of Darwinian evolution and the inclusion of major transitions. Together all these topics form a Gordian knot that makes it difficult to organise the discussion in such a way that questions can be answered one by one. How can such challenges be dealt with?

4.1.2 Goals and Strategy

The major goal of the current chapter is to provide a detailed analysis of Darwinian evolution with the aim of gaining a fundamental object-based understanding of the concept. The idea is that such understanding can later be used as a basis for extensions and generalisations. With such goals in mind, we decided to deal with the question of how Darwinian evolution can be defined as if it exists of two parts, the first focusing on a definition-oriented analysis, and the second on an application-oriented analysis.

The definition-oriented analysis aims at the identification of the theoretical criteria that a concept of Darwinian evolution should meet. The current strategy for the identification and integration of such criteria was inspired by Stoelhorst (2008) stating that: 'Clarification of the *explananda* of Darwinism is logically prior to the question whether its *explanantia* can be generalised to other domains or not'. In other words, it must be known which combination of phenomena will be viewed as evolution, before the causes of such phenomena can be identified and phrased in a general way. While in the literature various listings/summaries of criteria, such as reproduction, variation and selection, can be found that define evolution, it is difficult to evaluate whether or not such listings offer necessary and sufficient criteria. What makes such an evaluation problematic is that on the one hand the criteria are under suspect of being of different kinds, e.g., process or product, while on the other hand a framework is lacking for the integration of the criteria into something that in total can be viewed as a representation of Darwinian evolution. To deal with this challenge, a conceptual approach is needed that defines Darwinian evolution as a combination of the phenomena that cause it, the explanantia and the phenomena that result from it, the explananda, while there must be space in this definition for aspects that are processes as well as aspects that are products. To relate the *explananda* and *explanantia* of Darwinian evolution, we will use the fundamental methodology of graph-theory.

The application-oriented analysis focuses on the identification of a model for Darwinian evolution at its smallest scale. It is hypothesised that the irreducible simplicity of such a smallest scale model will offer a solid foundation for extensions and generalisations, of which examples will be discussed in Chap. 6. To define Darwinian evolution at the smallest scale, we use graph theory. The use of graph theory for the analysis of Darwinian evolution forms a standard technique in the population-based literature (Godfrey-Smith 2009). In some cases, descendence graphs are made, frequently without paying attention to the relationship between the shape of the graph, and the definition of Darwinian evolution. In other cases, the graphs illustrate a line of reasoning that is inherently linked to populations. In the latter case, the graphs that are used typically display two boxes, one containing a large number of dots representing the individuals in the parental population, and the other containing a large number of dots representing the offspring. The parents and offspring in the two boxes are connected through lines/arrows that represent descent. However, as soon as DNA/allele frequencies are calculated for the entire parent population and the entire offspring population the focus shifts from individuals to fractions of properties in populations. This implies that lines between individual parents and offspring are not actually taken into account. The close connection between the thinking about evolution and the thinking about populations is, for example, reflected in terms such as Darwinian microcosms and Darwinian subclans by Williams (1970) and the term Darwinian populations by Godfrey-Smith (2009).

The current approach aims at exploring a different path because it wilfully wants to pay attention to every specific parent-offspring relationship, and to use these as a basis for expressing the concept of Darwinian evolution in stringent object-based terms.

4.1.3 Imbedding

A broad range of scientific works have acted as a reference for the line of reasoning that is developed in the current book, including, e.g., in historical order: Malthus (1798), Darwin and Wallace (1858), Darwin (1859), Spencer (1891), Fisher (1930), Huxley (1942), Ghiselin (1969), Lewontin (1970), Price (1970), Popper (1972), Maynard Smith (1975), Hull (1980), Corning (1983), Ridley (1985), Salthe (1985), Mayr (1988), Plotkin (1994), Cziko (1995), Dennett (1995), Frank (1997), Bell (1997), Witting (1997), Mayr and Provine (1998), Michod (1999), Heylighen (1999), Jablonka and Lamb (2005), Okasha (2006), Pigliucci and Kaplan (2006), Kaila and Annila (2008), Brian Arthur (2009), Godfrey-Smith (2009), Rosenberg and Arp (2010), Pigliucci and Müller (2010), Losos (2013), Stearns (2013), and Ruse (2013).

4.1.4 Outline of This Chapter

Section 4.2 discusses basic choices that have to be made for defining the concept of Darwinian evolution. Section 4.3 introduces several ideas and concepts that allow for a graph-based analysis of the concept of evolution. Section 4.4 discusses the construction of the graph-pattern for Darwinian evolution at the smallest scale. Based on the current approach, specific graph-patterns can no longer be viewed as representing Darwinian evolution. Sect. 4.5 suggests new names for such graph-patterns. Finally, Sect. 4.6 discusses a selection of results.

4.2 Criteria for Defining Darwinian Evolution (Definition Oriented)

Discussions about definitions generally revolve around whether the criteria are necessary and sufficient. With respect to the definition of evolution, the criteria are frequently referred to as conditions that have to be met. To be necessary and sufficient, the conditions must include every relevant example, and exclude every non-relevant example. Godfrey-Smith (2007) has reviewed summaries/listings of conditions for Darwinian evolution, in other words evolution by natural selection, in the works of Lewontin (1970), Endler (1986) and Ridley (1996). Examples of such conditions are variation, heredity and fitness. Godfrey-Smith concludes that the investigated summaries either focus on conditions that will produce Darwinian evolution, which he refers to as a causal perspective, or on conditions for a process being a case of Darwinian evolution, which he refers to as a constitutive perspective. Additionally, we suggest that conditions also depend on the level of aggregation, e.g., object or population. If, for example, the population viewpoint is used, selection is linked to fitness, which should be understood as the probability of producing a specific number of offspring relative to the population average. When using an object-based viewpoint, however, selection is linked to a pattern in performance of the actual offspring of a parent. The object oriented and the population oriented viewpoints thus have a marked effect on the choice for using either fitness or offspring, respectively. As a wrapping up, it can be concluded that a total of three perspectives can be recognised:

1. Conditions of processes that cause Darwinian evolution (causal).
2. Conditions typical for examples of Darwinian evolution (constitutive).
3. The way conditions are related to a population-based viewpoint or an object-based viewpoint (aggregation).

The above three perspectives are not independent. If one chooses a specific level of aggregation, e.g., an object-based approach, this choice brings with it specific causal and constitutive conditions. In turn, specific causal conditions or constitutive conditions always imply a discussion at a well-defined level of aggregation. The conditions and the aggregation level thus depend on each other in both directions. An advantage of analysing evolution as a graph-pattern is now that this allows one to deal with such dependencies. In the current book chapter, we suggest that it is practical to first create a graph-pattern from the bottom up, using objects as the primary level of aggregation. As a next step, one can combine a range of such graph-patterns for the calculation of sums, averages and fractions associated with the population-based viewpoint. The object-based and population-based viewpoints also differ in their goals. The classical population-based viewpoint is the most well-known, and its goal is to offer a basis for calculations and predictions. And even though an object-based graph approach has not obtained much attention so far, we suggest that an object-based graph approach also has a role to play, namely as a theoretical foundation for defining the concept of Darwinian evolution.

4.3 Preparations for Creating a Graph-based Model for Darwinian Evolution (Application Oriented)

4.3.1 Kinds of Objects, Individuality and Levels of Material Complexity

To model Darwinian evolution by means of graph-theory, there must be clarity about which objects can be used in the graphs. This implies that a theory is needed for defining what will be viewed as an object.

It is not so easy to define an object. In the literature about this topic, many different and partially overlapping terms are in use, such as individual, organism, unit, token, Holon, entity, etc. Moreover, complex objects are generally constructed from less complex objects, for which reason the question of what is an object has much to do with hierarchy, and transitions between 'levels' of complexity. A well-known approach in biology dealing with biological levels is that of the so called "major evolutionary transitions" (Maynard Smith and Szathmáry 1995; Szathmáry 2015). According to Maynard Smith and Szathmáry one can speak of a major evolutionarytransition when the processes of cooperation and competition reduction produce an entity that can only replicate as a larger whole.

If one uses the criteria of the major evolutionary transitions, which are cooperation, competition reduction and reproduction as part of a larger whole, for the identification of individuality, many systems can be viewed as individuals, varying from a cell, to a bee colony and a population. These examples demonstrate that when individuality is based on major transitions, material unity is not used as a criterion. To be able to define also material unities, Metz (2013) has suggested the use of two sub-classes of individuals: primary individuals, which normally are called bodies, and meta-individuals, for example a family group. To define a primary individual one needs criteria for material unity.

A theory which defines material unity in a stringent way by focusing on the combination of functional and structural criteria is the Operator Theory (Jagers op Akkerhuis and van Straalen 1999). As has been explained in Chap. 2, the Operator Theory associates the presence of material and functional unity with the presence of dual closure, representing a combination of structural and functional closures. The concepts of closure, dual closure, and operator are viewed as the axiomatic basis of the Operator Theory. An example of a dual closure is offered by the bacterial cell, where the structural closure is represented by the membrane and the functional closure by the autocatalytic chemistry. In Chap. 2 also the example of the dual closure of multicellularity was explained, which combines the functional closure of connected plasma's and the structural closure of a shared cell membrane.

4.3.2 Naming Transitions Within and Between (Sub-)kinds of Operators

To improve clarity of discussions, every operator can be named after its kind in the operator hierarchy, e.g., an atom, a molecule, a cell, a multicellular, etc. More specific selections can be addressed as sub-kinds, such as Helium atoms, and Sparrow hawks. From this basis, changes within and between kinds can be addressed. For example, when a mutation changes the DNA of a bacterium, this represents a change within the operator kind, or WOK change. More specifically, it is possible that the change did not affect the species of the bacterium because it occurred within the operator sub-kind, and will be called a WOSK change. A change between operator sub-kinds is called a BOSK, for example radioactive decay from one atom species to another. And when two cells merge to form an endosymbiont operator, such an event will be called a change between operator kinds, or BOK. BOK changes occur in succession during some developmental histories, for example when a human female produces an ovum, or when a unicellular zygote develops into a multicellular blastula during human embryogenesis.

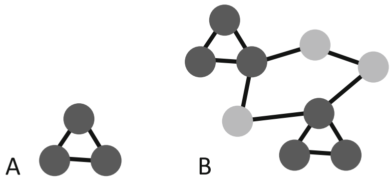


Fig. 4.1 (**a**) A graph-pattern with three nodes. (**b**) A larger graph which contains two examples of the small graph-pattern

4.3.3 Graph and Pattern

In this chapter, the concept of Darwinian evolution is analysed by means of graph-theory. Basically, a graph is a drawing of objects and relationships, represented by dots, called nodes, and lines, called edges. A specific combination of dots and lines is named a graph-pattern (Fig. 4.1a) (e.g., Klukas et al. 2005). A graph-pattern offers a practical analytic tool for various reasons: (1) it respects all underlying relationships, (2) it can take into account every object involved, (3) it can be used to decompose a large graph into (sub)patterns (see Fig. 4.1b) and (4) assuming that specific limiting conditions are met, the same graph-pattern applies to different kinds of objects and different kinds of relationships, because of which a graph-pattern is to some degree invariant. Before one can apply graph-theory for defining Darwinian evolution, both the relationships and objects must be specified. When, in the context of Darwinian evolution, we speak about a graph-pattern in this book, this use focuses on an object-based approach. This use of the term pattern must be distinguished from more general uses, such as the pattern that can be observed in the sequence of stages that occur during phenotypic development (Meyen 1973) and the pattern that functionally similar properties, such the torpedo shape of fish and dolphins, occur in species of taxonomically different branches in the tree of life, a phenomenon known as convergence.

4.3.4 Relationships in Evolution Graphs: Processes and Evaluations

In a graph, the objects are connected through relationships. Here, the focus is on two kinds of relationships which are defined axiomatically: dynamic relationships and static relationships. A dynamic relationship indicates a temporal change in a state. Examples of dynamic relationships are: is produced by, does refer to, e.g., reproduction and copying, moves, consumes, and is ageing. Henceforth, any singular dynamic relationship in a graph is referred to as a *process*. A sequence of combined processes, e.g., moving home, is called an abstract process, because it involves several events which do not take place at the same time or at the same place, but which conceptually, and thus at a higher level of abstraction, can be viewed as an overall process.

In contrast to a dynamic relationship, a static relationship describes a non-temporal aspect, such as a position, in time and/or space, or a difference. If two objects are different they represent the graph-pattern of variation. A static relationship does not represent a process. Instead, a static relationship is viewed as an evaluation.

Sometimes a graph combines dynamic and static relationships. For example, two reproduction events (dynamic) can lead to two offspring, while the observation that such offspring differ in their properties represents an evaluation (static). According to the reasoning suggested so far, a graph-pattern which combines a dynamic and a static relationship does represent more than a process, and will be addressed as a mixed graph-pattern. A mixed graph-pattern offers a filter which allows the identification of specific dynamics that comply with specific evaluative criteria.

4.3.5 Derivation and Selection: Two Fundamental Relationships Relevant for Darwinian Evolution

The goal of this book is to create definitions that are general. To define Darwinian evolution such that the approach can be generalised, we will make use of an object-based graph-pattern. For the generalisation/elaboration of a graph-pattern it must be clarified what are the objects in the graph, and what are the relationships, what are the objects in the graph, and what are the relationships. The kinds of objects that can take part in a graph were discussed in Sect. 4.3.1, and the kinds of relationships were discussed in Sect. 4.3.4. While using the graph-pattern as a means for creating a link between the *explanantia* and *explananda* of evolution (sect. 4.1.2), we will focus here on two different kinds of relationships in a graph of Darwinian evolution:

1. The production of next generation objects (a dynamic relationship that will be referred to as derivation).
2. The occurrence of a differential pattern in the production of next generation objects (a static relationship that is fundamental for the concepts of variation, selection and adaptation).

Derivation: A Dynamic Relationship Fundamental to Darwinian Evolution

If we want to generalise the concept of evolution, a way must be found to translate the biological concept of reproduction to another concept that indicates the production of new units also in non-biological contexts. As an umbrella concept for different means of producing one or more next generation objects this book will make use of the word derivation. Derivation axiomatically stands for all the processes which in the literature are indicated as reproduction, replication, budding, copying, imitation, etc. Derivation must not necessarily be performed by an object itself. For example, viral DNA may be derived by a cell, and a picture may be derived by a copying machine. Such non-autonomous forms of derivation have been named scaffolded processes by Godfrey-Smith (2009). An obligatory demand for derivation is that from a specific moment in time, the original object and the derived object can be counted as separate entities. The requirement that objects can be counted as separate entities is supported by the use of operators at different levels of complexity. However, when comparing the derivation of organisms, the derivation of quarks, hadrons, atoms and molecules requires a separate treatment, which will be discussed in Chap. 6.

The reason why derivation holds a central position in the current reasoning is that a range of concepts which are frequently used in discussions about evolution depend on it, including variation, descent, heredity and information. Firstly, derivation may lead to the difference-pattern of variation if next generation objects show differences in structure.

Secondly, derivation defines descent, because a derivation process starts with an original, and the next generation objects represent the descendants.

Thirdly, heredity comes into play when derivation leads to the transfer of a structure from the original object to a next generation object. Examples of these kinds of transferred structures are, e.g., copies of DNA, mitochondria, membrane material, etc.

Fourthly, properties which during derivation are transferred from the original to the next generation object can be viewed as information. With respect to the definition of the concept of information, the viewpoint of Checkland and Scholes (1990) is followed here, stating that information applies to data which can be endowed a meaning in a context. The context for the information value of a transferred structure may lay in its contribution to various processes which increase the persistence of the object and/or the derivation capacity of the object.

Derivation processes can occur in many different ways, and may involve different mechanisms through which properties can be transferred between generations, for example:

1. A property of an object can be transferred with or without a specific amount of change. This applies, e.g., to mutations and epigenetic coding of DNA, to the number of mitochondria, to specific membrane material of a cell, etc.
2. A structure can be present in the original without that it is ever transferred. Here one may think of phenotypically obtained properties such as a thick winter fur.
3. An original can introduce a new property in the next generation object during its derivation. Examples of this process are, e.g., the induction of hormone levels in a birds-egg, and epigenetic methylation of the DNA.
4. A novel property can form autonomously within the newly formed object (a mutation may occur selectively in the second generation object during derivation).
5. Some organisational properties may not be transferred. For example, when a multicellular organism involves in derivation, it will produce unicellular *ovi* or *spermi* which lack the multicellular construction. Because it allows one to deal with changes in properties during derivation in a structured way, the concept of derivation will be used as a technical foundation for later extension of Darwinian Theory.

Derivation processes differ from combination processes. In the current text combination processes will either be associated with the production of an object of the same kind, or with between operator kind (BOK) transitions. When an *ovum* and a *semen* fuse this is an example where the product is of the same kind as the initial cells (WOK transition). And when plasma connections form between cells and a multicellular is formed, this represents a BOK transition. If cells lack plasma connections, as in the slug-shape of the cellular slime mould *Dictyostelium discoideum*, the result is not viewed by the Operator Theory as a form of combination, but is viewed as a compound object (a group of cells). BOK transitions also occur in the abiotic world, for example when atoms form a molecule.

In addition to structure/information that is passed on to the next generation during the derivation process, an original can also pass on structure/information to a next generation object after the derivation process. This can take place in the form of, e.g., development in the uterus, horizontal DNA transfer or the horizontal transfer of ideas during learning. When the passing onto a next generation object takes place after derivation, one can speak of post-derivational transfer. Together, derivational and post-derivational transfer between objects forms the inspiration for dual inheritance theory (Boyd and Richerson 1985).

Derivation will generally lead to objects which classify as the same kind, for example when a bacterium produces a next generation bacterium. However, derivation may also lead to an object of a less complex kind, for example when a multicellular produces a unicellular *ovum* or *semen*. Which kind-relationships are considered relevant in a specific derivation process depends on conscious choices, for which one can make practical use of the Operator Theory. For example, one can decide that a derivation process which starts with an organism must always produce an organism. Now the derivation may describe how a multicellular organism with a neural network produces a unicellular ovum, which is an organism according to the Operator Theory. Which different kinds of operators can be considered organisms was discussed in Sect. 2.7.2. In natural processes there will generally be mechanisms involved through which the derived objects will be of a similar kind as their originals. After all, if an organism produces faeces this will not be viewed as a derived object. In the case of scaffolded derivation, however, the things that are produced using the original as an inspiration can differ in many aspects from the original. Here, one encounters the logical limits of the use of kinds in a derivation process.

In the current chapter derivation is closely linked to objects. As was discussed in Sect. 2.3 there are various reasons for viewing the operators as elementary kinds of objects. Yet, operators are not the only possible objects, because also concepts and artefacts, such as hammers, cars, etc., could, with some limitations, comply with an object-based graph. Such objects which are not operators may potentially bridge the gap between biology and the social sciences. A discussion of such options is very interesting, but deserves a study of its own. A consequence of an operator-based perspective is that any higher-level *explananda*, such the divergence of species, are viewed as phenomena that emerge from the underlying dynamics of operators.

Selection: A Static Relationship Fundamental to Darwinian Evolution

Is derivation a sufficient foundation for Darwinian evolution? After all, derivation by itself already causes a form of unrolling which can lead to descent, variation, inheritance, etc. Would derivational unrolling in the interpretation of the production of variable next generation objects be a sufficient description of the *explananda* of Darwinian evolution, if these explananda are, e.g., the origin of species, adaptive fit, the emergence of heterogeneity from common origins, or the accumulation of design? It has, for example, been discussed that species can form without selection (Maturana-Romesin and Mpodozis 2000). But there is one aspect of Darwinian evolution that cannot be explained in this way, namely *adaptive fit*. Adaptive fit and selection are closely related terms. When viewed from the perspective of the survivors that fit in with the system around them we can speak of adaptive fit. This fitting can be viewed as the mirror image of the organisms that do not fit with the environment and perform badly. When viewed from the perspective of the losers that did not fit in, the result is called selection. This deduction demonstrates that adaptation and selection can be viewed as two sides of the same coin. In the below we will focus on the selection aspect, which is generally viewed as being a cause of Darwinian evolution, while adaptive fit is viewed as a result.

Darwin (1859, pp 80–81) defined selection as: ‘This preservation of favourable variations and the rejection of injurious variations, I call natural selection’. Darwin thus defined selection as a differential measure, in the sense that the better a variation fits with the environment, the higher its chance of being preserved, and the lower the chance of it being rejected. The concept of selection thus refers to a comparison between variations. If we now view variations as relating to organisms, this implies that the death of some organisms is linked to special properties they have, and is compared with the death of some other organisms that lack such properties. An important conclusion can be drawn from this, namely that selection does not refer to death per se, but to property related *variance* in the chances of mortality when comparing between two or more organisms that have different properties.In this book the (static) difference relationship of selection will be viewed as an axiom that contributes to the definition of Darwinian evolution.

The realisation that selection represents a differential relationship is fundamental for a proper understanding of the concept. But differentiality is not the only relevant aspect of selection that deserves attention. Another aspect of selection that requires discussion is the existence of two *kinds* of derivation dynamics that are linked to different definitions of selection. The first kind of dynamics can be observed when every object realises derivation. This kind of dynamics will be referred to as full derivation. In the case of full derivation, every object produces at least one next generation object. Because of this the number of objects in the next generation can never decrease. Diversity is likely to be constant or to increase, because a property can only exit the population if it is lost during derivation or if it is changed to become another property. In a system where every object realises derivation, the only measure one can use for selection is the number of objects that are derived.

This number can differ between objects, but is always at least one. This number represents a continuous measure ranging from one to many.

The second kind of dynamics occurs when in the next generation one or more objects fail to realise derivation in the sense that derivation did not take place before disintegration of the object. We will refer to this kind of dynamics as partial derivation. In the case of partial derivation one can choose either to base selection on the occurrence or non-occurrence of derivation, or to base selection on the number of derived objects. Firstly, if one uses the (non-)occurrence of derivation, this represents a discrete binary variable. The use of a binary variable does not represent a numerical approach, but a logical approach, because it results in the logical classes yes or no. If the result is ‘no’, an object did not realise derivation during its existence. To address this option we will use the concept of failure of derivation. Secondly, one could also choose to base selection on a numerical measure, namely the number of derived objects. This number is represented by a continuous value ranging from zero to many. In the case of partial derivation dynamics, objects can fail to realise derivation, and this may result in an increase or decrease of the population and of diversity.

In this book, we aim at approaches that have general applicability. From this point of view it may seem attractive to base selection on a measure that can be applied with equal success to partial derivation dynamics and to full derivation dynamics. It is possible to in both cases base selection on the number of derived objects. However, this would result in an *approximation* of a general measure. After all, the choice for a numerical measure implies that one handles cases of partial derivation in the same way as cases of full derivation, even though an analysis of partial derivation may both involve numbers from 0 to many, and a logical value of yes/no, while full derivation can only be analysed using the numbers from 1 to many. On first sight, the use of a numerical approach offers the impression that this leads to a general approach. Thus, even though the numerical approach seems general it is viewed here as directing the focus away from the differences between the full derivation dynamics and the partial derivation dynamics.

The simplicity that is created by using a numerical approach comes at a price. The price that is paid is in fact twofold. Firstly, when using a numerical approach one can no longer apply the binary measure of failure of derivation, even though the use of a binary measure would represent the simplest approach. Secondly, even though the numerical measure does seem to unify the two approaches, it creates a mixed logic if we aim at representing selection in the simplest way. The reason is that a numerical approach depicts full derivation as 1 or N (N being any large integer), and partial derivation as 0 or N. Of these two cases, full derivation has no simple binary representation, while partial derivation can be expressed in a simple binary way if one focuses on the success or failure of derivation. This implies that if the goal is to create the simplest representation of a selection pattern, the possibilities differ for full derivation and partial derivation. Accordingly, it would lead to a logically incorrect result if one would treat partial derivation, and full derivation using the same measure.

A major goal of this book is to create stringent and simple definitions. The pursuit of this goal has several consequences. Firstly, in the case of partial derivation, we prefer the use of the binary measure of failure of derivation, because it is less complicated to evaluate the occurrence of reproduction than to have to count the number of offspring. Secondly, the use of one single measure for partial and full derivation would mix a method that uses a binary logical measure for selection (after translation to numerical values) with a continuous numerical measure for selection, respectively. The mixed criteria for selection would differ in their kind and simplicity, which would be undesirable results in the light of the current quest for logically uniform approaches. Thirdly, Darwin (1859, pp 80–81) viewed selection as the '… preservation of favourable variations and the rejection of injurious variations …' Knowing that Darwin's work was inspired by Malthus (1798) on overpopulation, we think that it is quite safe to assume that when Darwin referred to an object being rejected he meant that the object would not realise derivation during its existence. In the case of full derivation, however, it is difficult to imagine how one could apply rejection now that even the most unfavourable variations are not rejected because every object realises derivation. The only thing that can happen in a context without rejection is that unfavourable variations can become less numerous. By combining these arguments, we see three reasons for selecting the binary measure of failure of derivation as the basis for a simple pattern of selection. As will be explained in Chap. 6, basing selection on a binary measure will also create a stringent foundation for extrapolations.

A far-reaching consequence of using a binary measure for selection is that cases of full derivation no longer represent Darwinian evolution, regardless of whether or not the objects have one or many offspring. This implies that an alternative naming must be developed for graph-patterns in which all objects realise derivation. This subject will be discussed in Sect. 4.5.

In addition to discussing the important difference between a binary and a continuous measure for selection, we must also pay attention to stochasticity. In a system with stochastic effects, the relationship between the properties of an object and its derivation is to some degree unpredictable. There are two reasons for this. Firstly, if organisms have specific properties that would in principle cause the pattern of selection, the same properties may by chance fail to cause such a pattern. Secondly, if organisms have properties that would not normally cause a pattern of selection, for which reason these properties are called neutral, these may by chance produce a pattern of selection. As a synchronic analysis of the pattern of Darwinian evolution implies that there is no prescience about how a property will affect derivation, one can only base conclusions about the graph-pattern of selection on the de facto observation of properties and derivation events. This implies that stochastic noise must be accepted as is.

It can be deduced from these considerations that if the graph-pattern of Darwinian evolution is produced by a system that has no stochastic effects, the de facto graph-pattern will always faithfully represent the pattern of selection. An example of such a situation is a computer environment where absolute criteria can be designed for deciding about whether or not a specific entity, e.g., a computer virus or a genetic algorithm, will be derived or not. In cases where stochastic effects are present, however, such as in ecosystems, the simplest graph-pattern will necessarily include stochastic effects.

Based on the argumentation so far, it is possible to use a graph-pattern as inspiration for a (preliminary) general definition of the concept of Darwinian evolution (which potentially may require further generalisation) as follows: *Darwinian evolution has taken place when derivation processes starting with a single original object lead to one or more generations of descendants, which in a specific generation can be shown to comply with the graph-pattern of selection, while selection is based on a binary variable*. The objects involved must always be of a kind which supports derivation and the emergence of the graph-pattern of selection. The current book focuses on objects of the kind operator.

The above concept of Darwinian evolution differs in two major ways from the viewpoint of evolution by natural selection (ENS; Endler 1986; Godfrey-Smith 2007; Watson 2012). Firstly, the current approach no longer views selectionas a cause of evolution, as is conventionally implied by phrases that speak about evolution *by/through* selection. Instead, the current approach views selection as a small graph-pattern that is part of the larger graph-pattern of evolution. Secondly, the current viewpoint is object-based (see also Sect. 4.3.3), whilst the viewpoint of ENS is based on populations.

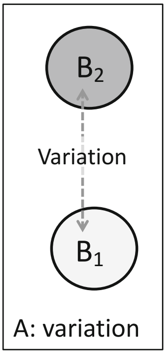
It is furthermore relevant that the definition of Darwinian evolution that was suggested above should not be mistaken for a biological approach. One obtains a biological version only if one uses organisms as the objects in evolutionary graph-patterns. In fact, the graph-pattern of Darwinian evolution is to a large degree general, because it is irrelevant whether objects are organisms, or are viruses, computer code, designs, etc. As the object-based graph-pattern for Darwinian evolution includes the graph-pattern of selection, the resulting approach extends to all similar patterns, but is not general in a broader sense, because it does not extend to unrolling processes named evolution that do not include the pattern of selection.

Now that fundamental aspects of a graph-pattern of Darwinian evolution have been identified and specified, the stage has been set for defining Darwinian evolution in its smallest form.

4.4 Darwinian Evolution at the Smallest Scale

The aim of this chapter is to construct a graph-pattern for Darwinian evolution at the smallest scale. Because of irreducible simplicity, such a graph-pattern can serve as a foundation for attempts at extension and generalisation (see Chap. 6). It may seem now as if the concept of evolution at the smallest scale is related to the concept of a Darwinian population in a minimal sense discussed by Godfrey-Smith (2009). However, the Darwinian population in a minimal sense focuses essentially on (Darwinian) populations, of which Darwinian individuals are part (Godfrey-Smith 2013). In the current approach, however, the focus is on objects and processes which may or may not cause an evolutionary pattern. Accordingly, in one graph pattern an object can on hindsight be viewed as a Darwinian individual when the graph-pattern it has helped to construct is of the Darwinian kind. Meanwhile, even when it carries

Fig. 4.2 The pattern of variation. B1 and B2 are objects that differ in a quality. The difference relationship is indicated by the *dashed arrow* named variation



out the same kind of processes, an object may not become a Darwinian individual in another graph-pattern. Based on this reasoning the question of whether or not an object can be called a Darwinian individual can only be answered on hindsight. To avoid that the current reasoning would have to include knowledge about future states of the system, we prefer to name the objects at any particular moment for what they are: objects. The only thing that in this chapter is viewed as being Darwinian is the graph-pattern.

Now that we aim at creating the graph-pattern of Darwinian evolution at the smallest scale, we will have to identify minimal representations of variation, selection and finally the smallest complete pattern of evolution.

A) A difference relationship: the pattern of variation.

We start with creating a pattern of variation (Fig. 4.2). The figure has two objects, B1 and B2, that differ in a single property (as is indicated by different shades of grey). The arrow named variation indicates that the variation aspect is assessed by observing the difference between the two objects B1 and B2. It should be noted that an assessment involves an evaluation, and for this reason represents a static relationship (Sect. 4.3.4).

B) Variation in property dependent derivation: the pattern of selection.

The pattern of selection can be viewed as an extended version of the pattern of variation. This is so, because the variation between the objects B1 and B2 is not only assessed for a single property, but also for how this property affects the realisation or failure of derivation. (an assessment represents an evaluation, which is viewed here as a static relationship, see Sect. 4.3.4). Above, three reasons have been offered why failure of derivation can best be used as the basic measure for the graph-pattern of selection (Sect. 4.3.5):

1. Failure of derivation offers the least complicated measure for selection.
2. The use of failure of derivation avoids the mixing of different logical approaches.
3. It may be logical to relate rejection to failure of derivation.

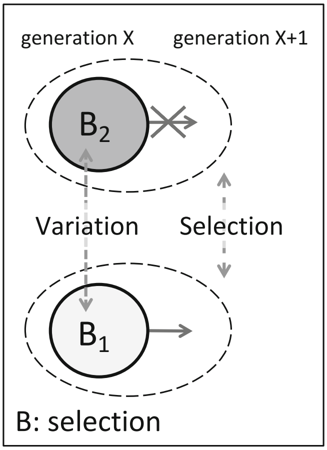


Fig. 4.3 The pattern of selection. The difference relationship between objects B1 and B2 is now assessed in relation to their property dependent capacity to realise derivation. *Dashed circle*: all the phenomena that are evaluated as part of the pattern of selection. The *dashed arrows* indicate the difference relationships of variation or selection. A *solid arrow* represents the production of a next generation object. A *cross* indicates that the object disintegrated before derivation took place

Based on the wish to define Darwinian evolution at the smallest scale, we focus here again on why failure of derivation offers the least complex method (Fig. 4.3). The use of failure of derivation does not require the counting of next generation objects, and is less complicated for this reason than if one counts the number of next generation objects (without knowing whether or not these will ever produce next generation objects), or if one counts the number of next generation objects which in turn produce next generation objects (analogous to reproductive success in biology).

C) A pattern of selection based on derived objects: Darwinian evolution.

The construction of a least complex example of Darwinian evolution implies that one selects the least complex properties of the objects, the least complex form of derivation and the least complex relationship with the environment. In the least complex case, there are no random effects disturbing the relationship between the properties of objects and the occurrence of failure of derivation. An example of such faithful behaviour is a genetic algorithm that makes use of a fixed selection criterion.

Based on the above preparations, the least complex graph-pattern of Darwinian evolution can be defined as follows: *derivation based on a single original leads to two derived objects which comply with the graph-pattern of selection based on failure of derivation*. The corresponding graph-pattern is that of Fig. 4.4. The graph-pattern represents an object A, which is viewed as the original. Original A may have been formed de novo, or may be a descendant of an earlier object. From A two objects are derived (B_1 and B_2). Objects of the kinds A and B are similar in a major kind, as was discussed in Sects. 4.3.2 and 4.3.5. B_1 and B_2 differ in the absence or

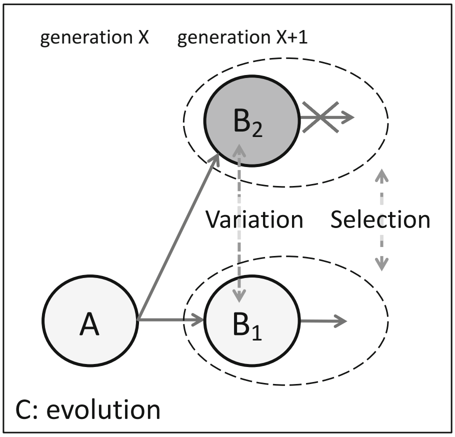


Fig. 4.4 The graph-pattern of Darwinian evolution at the smallest scale. A is an object in generation *X*, from which the objects B_1 and B_2 in generation $X+1$ are derived. A *solid arrow* represents the production of a next generation object. A *cross* indicates disintegration of the object before derivation. Dashed circles and arrows as in Fig. 4.3

presence of a single property. Selection is based on failure of derivation (as the least complex option). Because it makes use of descent, and generations, the graph-pattern of Darwinian evolution necessarily includes the aspect of time (dynamic relationship). An important conclusion can now be drawn, namely that Darwinian evolution combines two different *kinds* of relationships: 1.a dynamic graph-pattern based on the process of derivation, and 2. astatic graph-pattern represented by selection. The combination represents a mixed graph-pattern, which is **not a process**.

4.5 The Naming of Non-Darwinian Graph-Patterns

Above the concept of Darwinian evolution was defined as a graph-pattern which must include selection based on failure of derivation (FOD). Accordingly, a graph-pattern in which no organisms die before derivation does not represent Darwinian evolution. For example, if a bacterium splits, this leads to the emergence of two next-generation bacteria. When these split again, each of them produces two next generation bacteria. During these events, every object in every generation realises derivation, and the graph-pattern of selection (based on failure of derivation) does not occur. But if the graph-pattern does not represent selection, how must it be addressed? To answer this question, and to avoid the use of evolution *sensu lato*, the concept of branching is introduced. Branching implies that every object involved must realise derivation, while the environment can still have an impact on the branching. For example, a prolonged period of food shortage can cause female deer to be fertile every second year, instead of every year. Due to a lack of food, fertility is lower, and fewer offspring are produced. Such impact does not represent selection (no failure of derivation is observed), but will be addressed as inhibition, in this case the inhibition of fertility.

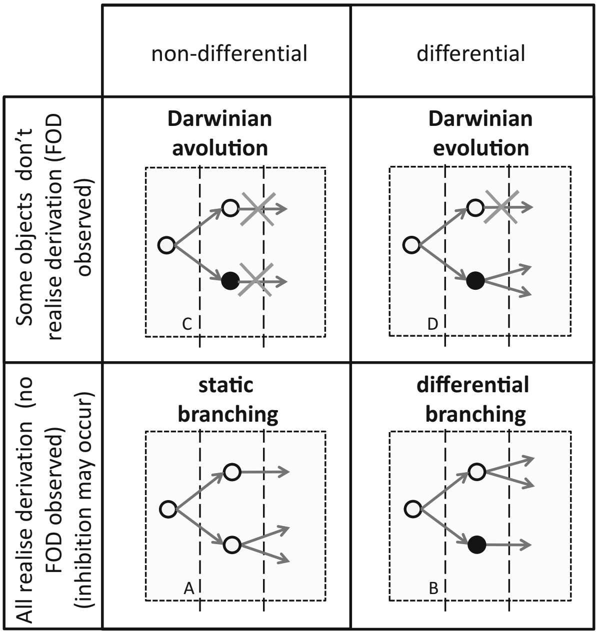


Fig. 4.5 A classification of graph-patterns of descent with and without failure of derivation, and with and without differentiality. *FOD* failure of derivation. A *solid arrow* indicates derivation. A *cross* indicates disintegration of the object before derivation. Black and white descendants represent the graph-pattern of variation

As Fig. 4.5 indicates the above reasoning results in two pairs of options. Firstly, if objects always realise derivation (no failure of derivation is observed), the graph-pattern is referred to as branching. Branching is related to two distinct graph-patterns:

1. Offspring production is not differential, named static branching.
2. Offspring production is differential, named differential branching.

Secondly, if failure of derivation occurs, two graph-patterns can be distinguished.

3. Failure of derivation occurs in a differential graph-pattern, named *Darwinian evolution*.
4. Failure of derivation occurs in a non-differential graph-pattern. If this occurs, the pattern is named *Darwinian avolution*. Darwinian avolution is not a typographical error, but refers to a new concept. While Darwinian evolution refers to differential branching with mortality, Darwinian avolution refers to non-differential branching with mortality.

Accordingly, the following four non-overlapping options are distinguished: static branching, differential branching, Darwinian avolution and Darwinian evolution. The four graph-patterns differ in the effects on the properties in a population.

By distinguishing between these four kinds of graph-patterns, transparency in discussions about evolution can be increased.

To further explain the current viewpoint, the relationships with neutral variation and random drift require clarification. It is relevant that neutral variations and their random drift may exist in the background of all four approaches and may occasionally coincide with a graph-pattern of evolution, Darwinian avolution, static branching or differential branching. Neutral mutations can create a reservoir of neutral structures, which after several changes can become active in the sense that they start affecting failure of derivation and/or inhibition (Kimura 1983).

It is important that the graph-patterns of branching or Darwinian avolution may eventually transform into the graph-pattern of Darwinian evolution. The transformation takes place in the generation in which the graph-pattern of selection can be observed. This implies that branching and Darwinian avolution can be viewed as phases that do not fit the pattern of Darwinian evolution and that in due time may (but not must) result in the graph-pattern of Darwinian evolution.

4.6 Discussion and Conclusions

Three subjects have been selected for this discussion section:

1. Why is it important to view variation, selection and Darwinian evolution as graph-patterns, instead of as processes?
2. How does the current object-based approach relate to population-based viewpoints?
3. The use of levels of selection as conceptual tools in evolutionary analyses.

The chapter ends with a summary of major conclusions.

4.6.1 Darwinian Evolution: A Process or a Mixed Graph-Pattern?

In the introduction it was indicated that several recent studies have suggested that selection is not a process (Endler 1986; Ghiselin 1969; Matthen and Ariew 2002; 2009; Corning and Szathmáry 2015). To explore such claims, the concepts of derivation, mortality, variation and selection were analysed in the current chapter with the help of graph-theory. Derivation and mortality both represent processes, therefore, any combination of these aspects can be viewed as representing a process too (dynamic relationship). Such a process fits the classical view of evolution as unrolling. However, our analyses furthermore indicated that, in an ontological sense, both variation and selection represent *difference relationships* which we indicated as evaluations (static relationship). A graph of Darwinian evolution therefore combines processes and evaluations. Such a combination was named a mixed graph-pattern (Sect. 4.3.4). Accordingly, the graph-pattern of Darwinian evolution does not comply with the classical viewpoint of unrolling, because the observation of variation and selection depend on evaluations carried out by humans. We repeat that such evaluations are not part of the process of evolutionary unrolling, but instead represent mental moulds that are mapped onto the process.

The change in perspective from viewing Darwinian evolution as a process, to viewing Darwinian evolution as a mixed graph-pattern sheds new light on attempts at measuring Darwinian evolution by means of experimental observations. If one uses this novel viewpoint it becomes easy to demonstrate the occurrence of Darwinian evolution, because the task transforms to proving that generations of objects comply with a specific graph-pattern. In contrast, the novel insights imply that, in a technical sense, any attempt at observing Darwinian evolution as a general process in nature (in terms of Sect. 4.3.4) represents a conceptually misdirected practice. Basically, the reason for this is that amidst all of the patterns produced by processes in nature, such as branching, differential branching, Darwinian avolution and Darwinian evolution, one can only classify the outcome of a specific subset of events as the pattern of Darwinian evolution. This also implies that it is impossible to say whether or not a situation represents a case of Darwinian evolution as long as the presence of the pattern of selection is not confirmed.

4.6.2 Population-Based Approaches

While it is possible to imagine a graph-pattern of Darwinian evolution at the smallest scale that does not include random effects, for example when the criteria for failure of derivation are of a theoretical kind, such as in some programmed genetic algorithms, a de facto graph-pattern of selection will generally include random effects (Lenormand et al. 2008). Due to random effects a specific graph-pattern, for example of the offspring production by a single mother, can deviate from the average selection pattern in a population at large. To deal with this, population models of evolution necessarily make use of averages based on large numbers of objects (Price 1970; Frank 1997; Rice 2008). While the focus on population-based averages forms a necessary basis for predictive calculations of the outcome of Darwinian evolution, we suggest that such averages may not offer a suitable basis for defining the *concept* of Darwinian evolution, for three reasons.

Firstly, based on the dynamic perspective, it is frequently suggested that populations evolve, or that species evolve. In the current viewpoint, Darwinian evolution is no longer viewed as a process, but as a graph pattern, and neither a species, nor a population, nor an object can on its own represent the Darwinian graph-pattern. Moreover, organisms and populations are entities of two different kinds. To clearly identify these kinds, one can use the logic of the Operator Theory, which advocates that organisms are objects of the kind operator, while populations are groupings of the kind interaction system. And while operators, such as organisms, can be used as the nodes in an object-based graph-pattern of Darwinian evolution (Chaps. 4 and 6), the same does not hold for interaction systems, such as populations, or compound objects. This does not mean that operators are the only objects that can be viewed as the nodes in an object-based graph, because ideas, such as ideas about being part of a behavioural group, may under special conditions comply with the graph-pattern of Darwinian evolution too (it is beyond the scope of this book to discuss the evolution of concepts in detail).

Secondly, if one makes use of populations of organisms, and defines Darwinian evolution as a change in DNA/allele frequencies of a population, one implicitly lumps different kinds of underlying object-based graph-patterns, such as Darwinian evolution, Darwinian avolution, branching and differential branching. In addition to this, organisms can migrate into or out of the area and in this way affect the DNA/allele frequencies without there being clarity about whether or not such organisms participate in any graph-pattern of Darwinian evolution. Technically speaking, the population approach is not conceptually homogenous because it lumps different *kinds* of graph-patterns and processes. While such inhomogeneity may rarely be problematic for the calculation of average trends, it is undesirable if the aim is to define the *concept* of Darwinian evolution.

Thirdly, the population approach defines Darwinian evolution as a measure, whilst the conceptual approach that is suggested in this chapter defines Darwinian evolution as a graph-pattern. This difference in viewpoints leads to various kinds of ambiguity. Firstly, the two uses of Darwinian evolution represent a confusing kind of homonymy. To avoid such homonymy, one may for example use the term of change in DNA/allele fractions in connection to a *measure* for evolution, and use the term Darwinian evolution in connection to the *conceptual* definition. Secondly, it is confusing that conflicting verdicts can be reached if one compares the population-based measure for evolution and the graph-pattern-based definition of Darwinian evolution. As an illustration, we will discuss the example of a single original blue object, which produces two derived objects, one blue and one red, after which only the blue one realises derivation. If one now calculates percentages, the single original can be viewed as a small population that is 100 % blue, and in the next generation, the percentage of surviving derived objects is again 100 % blue (only the red one died). When viewed from the perspective of changes in DNA/allele fractions over generations, no change in percentage has occurred. Accordingly one would conclude that no Darwinian evolution occurred. However, when applying the object-based approach, all the criteria for a Darwinian graph-pattern for evolution are met, because of the occurrence of derivation and a differential pattern of failure of derivation in the next generation, and the verdict would be that the pattern is an example of Darwinian evolution.

4.6.3 Viewing Levels of Selection as Conceptual Tools

Frequently it is assumed that selection can ‘act on’ different kinds of things, such as a cell in a fish, an entire fish, or a school of fish. The reason for this may be that from the population perspective it is possible to imagine three kinds of populations, either a population of cells in your body, a population of fishes in a pool, and a population of schools of fishes. And since cells aggregate to form fish, and fish aggregate to form schools, the aggregation events are used as a means to identify conceptual levels that selection can act on. While this approach is perfectly acceptable from a theoretic perspective, the use of a pattern of Darwinian evolution has several implications for what can or cannot be viewed as a level. The main reason is that the nodes in an object-based graph for Darwinian evolution primarily must be objects. And as has been discussed in Sect. 4.3.1 the Operator Theory offers new ideas about what can be viewed as an 'object'. Using the concept of the operator as a basis, the Operator Theory looks at the ecosystem as if any organism in it interacts on a level basis with all the other objects in the ecosystem (Jagers op Akkerhuis 2008). At different moments in time, a hare interacts with the grass it eats, the stones it sits on, the predator it flees from, the partner it mates with, etc. As is also apparent from Fig. 2.4 the Operator Theory views the distinction of levels in ecosystem as conceptual groupings, which arise if one focuses specifically on how for example deer interact with other deer and in this way form a herd, and subsequently uses higher order groupings to conclude that herds interact to form a population, that populations interact to form a community, etc. Although in many people's minds herds, populations and communities seem to almost take the position of lower level physical objects, contributing to higher level physical objects, one can rarely observe a corresponding physical construction in nature. It is interesting to observe that our minds seem to conflate a theoretical construct of increasingly inclusive, abstract concepts, namely the abstract sets to which we assign the organisms (herds, populations, communities, ecosystems), with an analysis of the physical structure inside an operator or inside a compound object.

The perspective of the Operator Theory thus views levels of selection as representing different—and not necessarily nested—conceptual groupings that are based on a selection of kinds of interactions that individual organisms have with each other and with their environment. Instead of on levels, the operator viewpoint focuses on impacts, and on factors causing releases from impacts, that in combination act on every individual. The final influence that is experienced by any organism at any moment is the sum of all the interactions with other objects that cause impacts or cause a release from impacts. From this perspective, the levels of selection can be viewed as conceptual tools that allow a simplification of the analysis by a conscious grouping of all the different impacts on an organism into specific classes. The limits to such classes can in many cases be viewed as relative, because organisms can enter and leave a group. For example, a fish can swim alone, join a small school, the fish in the small school may join a large school and the fish in the large school may split apart and continue their ways as individual fish. In all such processes the school of fish takes the shape of a conceptual unity of variable size and composition.

An object-based representation of effects of crowding/grouping would now be to focus on stressors which push the physiology of a specific organism away from its physiological optimum in the sense that both the functioning below and above the optimum can be viewed as unfavourable, or stressed states. The further the organism is pushed away from its optimum, the more severely it is stressed. Both stressors and releases from stressors may originate from frequent contacts with organisms in the vicinity: think of how individual organisms in a herd of deer or in a school of fish compete with each other or help each other, from abiotic factors, such as temperature, and from organisms which are being encountered less frequently or even more or less randomly, e.g., the sudden appearance of a predator. The overall stress level of an organism is the sum of all the individual stressors and releases from stressors. According to this viewpoint the use of levels transforms into a summing up, an integral over time, of influences/stressors/stress-releases of different kinds, originating from all the different entities that an organism interacts with during a given period of time. The more stress, the less the chance that an organism will eventually realise derivation. And differences in the realisation of derivation will lead to the pattern of selection.

4.7 Conclusions

This chapter leads to the following conclusions:

1. An object-based graph-pattern offers an integrative platform for all aspects (objects, relationships, kinds of graph-patterns) relevant for a conceptual analysis of Darwinian evolution.
2. It was concluded that both variation and selection represent evaluations of differences. As the graph-pattern of Darwinian evolution includes derivation (a process; dynamic) and variation/selection (representing evaluations; static) it describes more than a process, and was named a mixed graph-pattern for this reason.
3. For object-based graph-patterns, it was demonstrated that there are relevant advantages to using a binary variable, instead of a quantitative variable, as the measure for selection. Examples of binary variables at different levels of abstraction are: the failure of reproduction in the case of organisms, the failure of derivation in the case of abiotic objects, and the failure of dual closure in the case of the emergence of new kinds of operators in the Operator Theory.
4. While population-based averages represent a practical means for the calculation and prediction of average *results* of evolution, a graph-pattern forms a necessary basis for defining the *concept* of evolution.
5. A focus on operators allows one to use well-defined objects as the basis for a graph-pattern of evolution.
6. The graph-pattern of Darwinian evolution translates into the following definition of the concept of evolution: *Darwinian evolution has taken place when derivation processes starting with a single original object lead to one or more generations of descendants, which in a specific generation can be shown to comply with the graph-pattern of selection, while selection is based on a binary variable.* This definition does not yet account for, e.g., the possibility of using higher lev-

els of conceptual aggregation in the form of specific kinds of objects, instead of the objets themselves, as nodes in the graph.

References

Aldrich HE, Hodgson GM, Hull DL, Knudsen T, Mokyr J, Vanberg VJ (2008) In defence of generalized Darwinism. J Evol Econ 18:577–596

Beinhocker ED (2006) The origin of wealth. Evolution, complexity, and the radical remaking of economics. Harvard Business School Press, Boston

Bell G (1997) Selection, the mechanism of evolution. Chapman and Hall, New York

Bickhard MH, Campbell DT (2003) Variations in variation and selection: the ubiquity of the variation-and-selective-retention ratchet in emergent organizational complexity. Found Sci 8:215–282

Blackmore S (1999) The meme machine. Oxford University Press, Oxford

Bonner JT (1974) On development: the biology of form. Harvard University Press, Cambridge, MA

Boyd R, Richerson PJ (1985) Culture and the evolutionary process. University of Chicago Press, Chicago

Brian Arthur W (2009) The nature of technology. What it is and how it evolves. Penguin, London, England

Brian Arthur W, Polak W (2006) The evolution of technology within a simple computer model. Complexity 11:23–31

Buskes C (2013) Darwinism extended: a survey of how the idea of cultural evolution evolved. Philosophia. http://link.springer.com/article/10.1007%2Fs11406-013-9415-8#

Buskes C (2015) Darwinizing culture: pitfalls and promises. Acta Bioteoretica. doi:10.1007/s10441-015-9247-y

Buss L (1987) The evolution of individuality. Princeton University Press, Princeton, N.J.

Campbell DT (1960) Blind variation and selective retention in creative thought as in other knowledge processes. Psychol Rev 67:380–400

Chaisson EJ (2001) Cosmic evolution: the rise of complexity in nature. Harvard University Press, Cambridge, MA

Checkland P, Scholes J (1990) Soft systems methodology in action. Wiley, Chichester, 329 pp

Corning PA (1983) The synergism hypothesis: a theory of progressive evolution. McGraw-Hill, New York

Corning PA, Szathmáry E (2015) "Synergistic selection": a Darwinian frame for the evolution of complexity. J Theor Biol 317:45–58

Cziko G (1995) Without miracles. Universal selection theory and the second Darwinian revolution. MIT Press, Cambridge, MA

Darwin C (1859) On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life, 1st edn. John Murray, London

Darwin C (1876) On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life, 6th edn. John Murray, London

Darwin C, Wallace AR (1858) On the tendency of species to form varieties; and on the perpetuation of varieties and species by natural means of selection. Zool J Linn Soc 3:46–50

Dawkins R (1976) The selfish gene. Oxford University Press, Oxford

Dawkins R (1983) Universal Darwinism. In: Brendall DS (ed) Evolution from molecules to man. Cambridge University Press, Cambridge, pp 403–425

Dennett DC (1995) Darwin's dangerous idea: evolution and the meanings of life. Simon and Schuster, New York

Depew DJ, Weber BH (2013) Challenging Darwinism: expanding, extending, replacing. In: Ruse M (ed) The Cambridge encyclopedia of Darwin and evolutionary thought. Cambridge University Press, Cambridge

Endler J (1986) Natural selection in the wild. Princeton University Press, Princeton, NJ, 336 pp

Fisher RA (1930) The genetical theory of natural selection. Oxford University Press, Oxford, xiv + 272 p

Frank SA (1997) The Price equation, Fisher's fundamental theorem, kin selection, and causal analysis. Evolution 51:1712–1729

Futuyma DJ (1998) Evolutionary biology, 3rd edn. Sinauer Associates Inc, Sunderland, MA

Ghiselin MT (1969) The triumph of the Darwinian method. University of California Press, Berkeley

Godfrey-Smith P (2007) Conditions for evolution by natural selection. J Philos 104:489–516

Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford

Godfrey-Smith P (2013) Darwinian individuals. In: Bouchard F, Huneman P (eds) From groups to individuals. Evolution and Emerging Individuality. MIT Press, Cambridge, MA

Hannon E, Lewens T (2013) Cultural evolution. In: Losos JB, Baum DA, Futuyma DJ, Hoekstra HE, Lenski RE, Moore AJ, Peichel CL, Schluter D, Whitlock MC (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Heylighen F (1999) The growth of structural and functional complexity during evolution. In: Heylighen F, Bollen J, Riegler A (eds) The evolution of complexity. Kluwer, Dordrecht, pp 17–44

Hodgson GM, Knudsen T (2006) Why we need a generalized Darwinism, and why generalized Darwinism is not enough. J Econ Behav Organ 61:1–19

Hull DL (1980) Individuality and selection. Annu Rev Ecol Evol Syst 11:311–332

Huxley JS (1942) Evolution: the modern synthesis. Harper, New York

Jablonka E, Lamb MJ (2005) Evolution in four dimensions: genetic, epigenetic, behavioral, and symbolic variation in the history of life. MIT Press, Cambridge, MA

Jagers op Akkerhuis GAJM (2001) Extrapolating a hierarchy of building block systems towards future neural network organisms. Acta Biotheor 49:171–189

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organization of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2010) The Operator Hierarchy, a chain of closures linking matter life and artificial intelligence. PhD thesis, Radboud University, Nijmegen

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego-bricks of nature: evolutionary transitions from fermions to neural networks. World Futures 53:329–345

Kaila VRI, Annila KA (2008) Natural selection for least action. Proc R Soc A 464:3055–3070

Kimura M (1983) The neutral theory of molecular evolution. Cambridge University Press, Cambridge, UK

Klukas C, Koschützki D, Schreiber F (2005) Graph-pattern analysis with PatternGravisto. J Graph Algorithms Appl 9:19–29

Laland K, Uller T, Feldman M, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J, Wray GA, Hoekstra HE, Futuyma DJ, Lenski RE, Mackay TFC, Schluter D, Strassmann JE (2014) Does evolutionary theory need a rethink? Nature 514:161–164

Laland KN, Uller T, Feldman MW, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J (2015) The extended evolutionary synthesis: its structure, assumptions and predictions. Proc R Soc Biol Sci 282(1813):20151019

Lenormand T, Roze D, Rousset F (2008) Stochasticity in evolution. Trends Ecol Evol 24:157–165

Levit GS, Hossfeld U, Witt U (2011) Can Darwinism be "Generalized" and of what use would this be? J Evol Econ 21:545–562

Lewontin RC (1970) The units of selection. Annu Rev Ecol Syst 1:1–18

Losos JB (2013) What is evolution? In: Losos JB, Baum DA, Futuyma DJ, Hoekstra HE, Lenski RE, Moore AJ, Peichel CL, Schluter D, Whitlock MC (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Malthus TR (1798) An essay on the principle of population. Johnson, London

Matthen M, Ariew A (2002) Two ways of thinking about fitness and natural selection. J Philos 99:55–83

Matthen M, Ariew A (2009) Selection and causation. Philos Sci 76:201–224

Maturana-Romesin H, Mpodozis J (2000) The origin of species by means of natural drift. Rev Chil Hist Nat 73:261–310

Maynard Smith J (1975) The theory of evolution, 3rd edn. Penguin, Harmondsworth

Maynard Smith J, Szathmáry E (1995) The major transitions in evolution. W.H. Freeman Spektrum, Oxford

Mayr E (1988) Toward a new philosophy of biology. Observations of an evolutionist. Harvard University Press, Cambridge

Mayr E, Provine WB (1998) The evolutionary synthesis: perspectives on the unification of biology. Harvard University Press, Cambridge, MA

Mesoudi A (2010) Evolutionary synthesis in the social sciences and humanities. Cult Sci 3(1)

Metcalfe JS (1998) Evolutionary concepts in relation to evolutionary economics. CRIC working paper no. 4

Metz JAJ (2013) On the concept of individual in ecology and evolution. J Math Biol 66:635–647

Meyen SV (1973) Plant morphology in its nomothetical aspects. Bot Rev 39:205–260

Michod REY (1999) Darwinian dynamics: evolutionary transitions in fitness and individuality. Princeton University Press, Princeton, NJ

Odling-Smee JF, Laland KN, Feldman MW (2003) Niche construction: the neglected process in evolution, Monographs in population biology 37. Princeton University Press, Princeton, NJ

Okasha S (2006) Evolution and the levels of selection. Oxford University Press, Oxford

Piepenbrock TF (2009) Toward a theory of the evolution of business ecosystems : enterprise architectures, competitive dynamics, firm performance and industrial co-evolution. MIT. http://hdl.handle.net/1721.1/57976

Pigliucci M (2007) Do we need an extended evolutionary synthesis? Evolution 61:2743–2749

Pigliucci M, Kaplan J (2006) Making sense of evolution: the conceptual foundations of evolutionary biology. University of Chicago Press, Chicago

Pigliucci M, Müller GB (2010) Evolution—the extended synthesis. The MIT press, Cambridge, MA

Plotkin HC (1994) Darwin machines and the nature of knowledge: concerning adaptations, instinct and the evolution of intelligence. Harvard University Press, Cambridge, MA

Popper KR (1972) Objective knowledge: an evolutionary approach. Oxford University Press, London

Price GR (1970) Selection and covariance. Nature 227:520–521

Ray TS (1995) Artificial life and the evolution of distributed processes. J Jpn Soc Artif Intell 10:213–221

Ray TS (2009) Artificial life programs and evolution. In: Ruse M, Travis J (eds) Companion to evolution. Harvard University Press, Cambridge, MA, pp 429–433

Rice SH (2008) A stochastic version of the Price equation reveals the interplay of deterministic and stochastic processes in evolution. BMC Evol Biol 8:262

Ridley M (1985) The problems of evolution. Oxford University Press, Oxford

Ridley M (1996) Evolution. Blackwell, Oxford

Rosenberg A, Arp R (2010) Philosophy of biology. An anthology. Wiley-Blackwell, Chichester, UK

Ruse M (ed) (2013) The Cambridge encyclopedia of Darwin and evolutionary thought. Cambridge University Press, Cambridge

Salthe S (1985) Evolving hierarchical systems: their structure and representation. Columbia University Press, New York

Spencer H (1891) Essays: scientific, political, and speculative. Library Edition, Vol 2. Containing Seven Essays not before republished, and various other Additions. Williams and Norgate, London

Stearns SC (2013) Natural selection, adaptation, and fitness; an overview. In: Losos JB et al (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Stebbins GL (1969) The basis for progressive evolution. University of North Carolina Press, Chapel Hill

Stoelhorst JW (2005) The naturalist view of universal Darwinism: an application to the evolutionary theory of the firm. In: Orillard M, Finch J (eds) Complexity and the economy. Edward Elgar, Cheltenham, pp 127–147

Stoelhorst JW (2008) The explanatory logic and ontological commitments of generalized Darwinism. J Econ Methodol 15:343–363

Stoelhorst JW (2010) The firm as a Darwin machine: how generalized Darwinism can further the development of an evolutionary theory of economic growth. Papers on Economics and Evolution #1019, Max Planck Institute of Economics, Jena

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. Proc Natl Acad Sci 112:10104–10111

Teilhard de Chardin P (1969) The future of man. Collins, London. (Original: Editions du Seuil V, Paris, 1946)

Watson RA (2012) Is evolution by natural selection the algorithm of biological evolution? Artif Life 13:121–128

Williams MB (1970) Deducing the consequences of evolution: a mathematical model? J Theor Biol 29:343–385

Witting L (1997) A general theory of evolution by means of selection by density dependent competitive interactions. Peregrine publishers, Arhus

Yaeger LS (1994) Computational genetics, physiology, metabolism, neural systems, learning, vision, and behavior or polyworld: life in a new context. In: Langton C (ed) Proceedings of the Artificial life III Conference. Addison-Wesley, Reading, MA, pp 263–298

Chapter 5
Reflections on the Graph Representation of Darwinian Evolution

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Abstract The proposal of Jagers op Akkerhuis et al. (Chap. 4) is that Darwinian evolution can better be discussed in terms of a graph-pattern than in terms of population-based frequencies of properties that change from one generation to the next. The authors suggest that the use of a graph-pattern can contribute to resolving current debates about extending and generalizing the concept of evolution, because a graph-pattern allows for detailed discussions of the objects, the relationships, and the patterns that constitute the concept of Darwinian evolution. We raise some questions about the currently suggested graph pattern, which—in our view—may require an additional generation. Furthermore, the use of a minimalistic and abstract graph-pattern raises questions about the links with several biologically relevant evolutionary principles including natural selection, mutation and recombination, development, and genetic drift and genetic bottlenecks. We ask the question whether a graph representation of Darwinian evolution can be extended in such a way that it sufficiently reflects this type of biological complexity. This, in our view, presents a challenge for the further development of Jagers op Akkerhuis' abstract representation of evolutionary theory.

5.1 Introduction

Jagers op Akkerhuis et al. (Chap. 4) present a novel conceptualization of evolution. Their—quite radical—point of view is that evolution is better discussed in terms of a pattern of relations between objects (individuals) than as a process of something developing in time. To formalize the relations, they propose that advantage can be taken of graph theory, a discipline of mathematics related to set theory. The attractiveness of this new approach is that it is easily generalized outside the evolution of living organisms to other situations where evolution plays a crucial role, for example

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_5

the evolution of physical objects, molecules, atoms, and subatomic particles. To try and erase the borders between such disciplines as atomic theory, chemistry, molecular biology, and ecology is a unique endeavor, and Jagers op Akkerhuis seems to be one of the few thinkers in science who is actually attempting this and trying to find the formalisms that are needed to cut across borders. In this respect, Jagers op Akkerhuis' approach is similar in spirit to Eiben and Smith (2015), who stretched the concept of evolution across biology, mathematics, and technology.

The generalized concept of evolution and its precise definition in terms of graph theory may also help to overcome discussions about possible tautologies and circular arguments that have plagued evolution for many years. Obviously, evolution as a scientific theory is testable and not tautological although some concepts can be presented as such, especially "survival of the fittest," if this is simplified to mean that the fittest is the one that survives. Philosophical analyses of evolutionary concepts can help to hone the concepts and clarify what evolution does and does not claim (Van der Steen 2000). We see the approach by Jagers op Akkerhuis et al. contributing to a tradition of methodological analysis and commentaries that have joined evolutionary science since the formulation of the "Modern Synthesis" developed by Julian Huxley and others, in the years 1935–1945.

5.2 Evolution as a Graph Pattern

We agree that the conceptual core of Darwinian evolution can be defined by means of a graph-pattern. This is shown in Fig. 4.4 in which the graph-patterns of variation, selection, and Darwinian evolution are drawn at the smallest scale. However, in our view, the use of the solid arrows in this figure is inconsistent. The solid arrows in the left part of Fig. 4.4 are drawn between objects A and B1, and between objects A and B2. This is in line with Sect. 4.3.3 in which the ontology of a graph is described as consisting out of objects and relationships connecting the objects. In this ontology there are two kinds of relationships, dynamic and static. The solid arrow is an example of a dynamic relationship and indicates a temporal change in a state and is referred to as a "process." Jagers op Akkerhuis et al. first example of dynamic relationships is: "is produced by" (e.g., by reproduction or copying). The solid arrows from object A to objects B1 and B2 are examples of the statement "object B is produced by object A."

The next solid lines in Fig. 4.4 start from object B1 and object B2, but reach no other object. Also, the solid arrow starting from object B1 contains a cross. This is explained in the subscript of Fig. 4.4 by the following statements: "A solid arrow represents the production of a next generation object. A cross indicates failure of derivation." The solid line starting form object B2 represents the production of a next-generation object, while in the case of B1 there is a cross indicating failure of derivation (e.g., reproduction). There are two problems concerning these solid lines. The first problem concerns the logic of testing empirical statements in science in general. It is empirically impossible to test "failure of derivation" because only refutation of "failure of derivation," by showing a successful derivation, is logically possible. Since we already have incorporated in generation x + 1 one, necessary, successful derivation, a second one would mean that we have a situation of differential branching in Fig. 4.4.

The second problem is about the difference between dynamic relationships and objects. The solid arrows originating from objects B1 and B2 have a different meaning than the solid arrows originating from object A1 because there is no dynamic relationship of the kind "C1 is produced by B2," or "Cn is not produced by B1." In this way, the solid arrow represents at the same time a dynamical relationship and an object, or a nonexistent object in the case of the crossed solid line. To avoid dynamic relationships becoming hybrids of dynamic relationships and objects, we suggest only the use of dynamic relationships that connect objects. This will strengthen Jagers op Akkerhuis et al.'s radical point of view that evolution is better discussed in terms of relations between objects (individuals) than as a process of something developing in time.

Our criticism changes Fig. 4.4 in two ways.[1] First, there is no crossed solid arrow from B1 to the right anymore. In general, an object without a solid line to the right has no derivation. In this way, selection is still based on a binary variable. Second, we need to add an additional generation, x + 2, in which an object C1 is connected by a solid arrow from B2. Using the graph-theory described in Sect. 4.3.4, the steps from A1, via B2 to C1, can be described as an "abstract process": a combination of processes. In this way, Darwinian evolution involves several events that do not take place at the same time or at the same place, but which conceptually (as an abstraction) can be viewed as an overall process.

5.3 Link with Evolutionary Narrative

A drawback of any methodological approach is that it tends to become highly abstract. By focusing on the essence of the argument, by explicitly striving for a representation "in the smallest form possible," superfluous contextual information is discarded; the need for ultrastringent definitions brings evolution back to its bare essence: in biology it is a graph representing the relationship between a parent and its offspring. However, in many cases, abstract concepts acquire their meaning within a certain context. The narrative environment of a theory, the stories, examples, failures, and successes provide meaning and aid understanding. Every teacher knows that difficult concepts are not learnt from definitions, but from stories, examples, and odd cases. This may especially hold for evolution, which, due to its partly historical nature, contains a good deal of natural history.

To illustrate the pitfall described above, we recapitulate how most biologists would respond, when asked to describe the concept of evolution. They most likely

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[1] The authors of this chapter thank van Straalen en Gremmen for their suggestions for creating a more consistent representation of the graphs. We fully agree, and have adapted all the graphs of evolutionary patterns that occur in later chapters of this book accordingly.

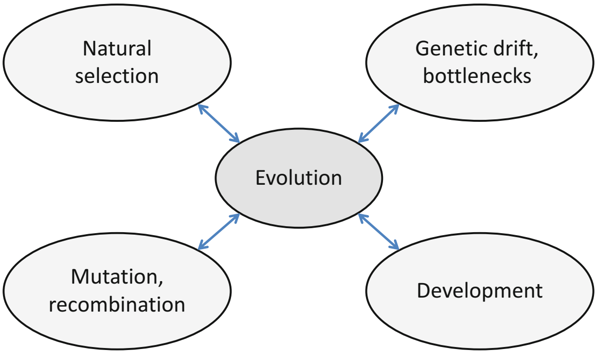

Fig. 5.1 An integrative view of evolution as recognized by most evolutionary biologists. Ecology, genetics, developmental biology and population genetics all contribute to explain evolution from four different complimentary angles

would indicate at least four different topics or areas of research that "have to do" with evolution (Fig. 5.1):

1. Natural selection
2. Mutation and recombination
3. Genetic drift
4. Development

These four topics are dealt with by ecology, genetics, population genetics, and developmental biology, resp., and they all have meaningful things to say about the current view on evolution.

Natural selection is the key concept indicated by Charles Darwin as the major force that shapes evolution. There is no biologist who doubts this (Dobzansky 1973). The evidence for natural selection in action, for organisms to change the genetic composition of their populations under specific ecological conditions, is overwhelming. Recently, it has been recognized that evolution and ecology also influence each other in eco-evolutionary feedbacks, implying that a theory of evolution cannot do without a theory of ecology. The ecological context of evolution and natural selection does not seem to be part of Jagers op Akkerhuis' representation of evolution at the smallest scale.

A large variety of molecular events, mutations, chromosome rearrangements, genome duplication, recombination, lateral gene transfer following endosymbiosis, to mention only the most important, are responsible for generating (in an undirected manner) the variation that is necessary for natural selection to act upon. Of special interest is sexuality, a trait common to almost all multicellular organisms which has caused many debates among evolutionists due to its unclear advantages for the individual. While the graph-pattern of Darwinian evolution at the smallest scale of Jagers op Akkerhuis' theory does not deal explicitly with the question how variability is generated and does not shed new light on the evolution of sexual recombination.

Many scientists have warned against an over-emphasis on Darwinian selection as the only process that shapes evolution. When selective advantages are small, mutation may be the most important driving force of evolution because new gene variants may become fixed in small populations irrespective of their selective value. Even disadvantageous alleles may come to dominate the population due to genetic drift or bottlenecks events (Lynch 2007; Nei 2007). Evolution includes a good deal of nonadaptive processes; we like to see more information about whether and how the evolutionary framework of Jagers op Akkerhuis is able to deal with them.

Finally, developmental constraints can be highly influential in phenotypic evolution. New body plans arise by mutations in the regulatory machinery that directs the development of an organism after fertilization. Since the embryo develops as a unified whole, changes in one aspect of development may cause grave changes in other developmental processes, thereby blurring an adaptive interpretation of the phenotype. Recently, a novel conceptual framework of evolution has been proposed that attempts to include development, inclusive inheritance, and niche construction (Laland et al. 2015). This type of integrative view seems not to be covered by Jagers op Akkerhuis' view of Darwinian evolution at the smallest scale.

Any biologist will recognize the four issues that we highlight in Fig. 5.1. The question is, can a graph representation of Darwinian evolution at the smallest scale, as indicated by Jagers op Akkerhuis in Chap. 4, be extended in such a way that it sufficiently reflects this type of complexity, the day-to-day complexity of evolutionary science? As we interpret the graph-pattern at the smallest scale, this raises questions about whether or not evolution can be defined, analyzed, and studied separate from ecology, genetics, population genetics, and developmental biology. In our view, the answering of such a question offers a challenge for the further development of Jagers op Akkerhuis' ultra-parsimonious theory of evolution.

References

Dobzansky T (1973) Nothing in biology makes sense except in the light of evolution. Am Biol Teacher 35:125–129

Eiben AE, Smith J (2015) From evolutionary computation to the evolution of things. Nature 521:476–482

Laland KN, Uller T, Feldman MW, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J (2015) The extended evolutionary synthesis: its structure, assumptions and predictions. Proc R Soc B 282:20151019

Lynch M (2007) The frailty of adaptive hypotheses for the origins of organismal complexity. Proc Natl Acad Sci U S A 104(Suppl 1):8597–8604

Nei M (2007) The new mutation theory of phenotypic evolution. Proc Natl Acad Sci U S A 104:12235–12242

Van der Steen WJ (2000) Evolution as natural history. A philosophical analysis. Praeger, Westport, 187 pp

Chapter 6
Generalising Darwinian Evolution by Using Its Smallest-Scale Representation as a Foundation

Gerard A.J.M. Jagers op Akkerhuis, Hendrik Pieter Spijkerboer, and Hans-Peter Koelewijn

> *'The controversy on the appropriate use of Darwinist concepts in evolutionary economics has been rekindled and modified by the idea of "Universal Darwinism" which has recently gained much attention among biologists and biologically-inclined philosophers. This proposition holds that all evolutionary processes share the same abstract structure of the Darwinist scheme of variation, selection and retention. Put differently, evolution outside the realm of biology is not argued to be similar to evolution in nature, but the proposition is that, at a sufficiently abstract level of analysis, evolutionary processes in different domains are identical in their basic structure (cf., e.g. Hull 1988; Dennett 1995)'(Buenstorf 2006)*

Abstract The Latin word *evolvere* means to unroll. As unrolling is a very general concept, the *sensu lato* interpretation of evolution has become a catchall for many different dynamic phenomena in nature. While zooming in on part of this broad context, this chapter focuses on the Darwinian kind of evolution. The structure of Darwinian evolution was analysed in Chap. 4, resulting in the identification of an object-based graph-pattern for Darwinian evolution at the smallest scale. The hypothesis of this book is that, because of its irreducible complexity, a definition at the smallest scale can serve as a reference for a range of extensions, which define a family of related patterns of Darwinian evolution. To test this hypothesis, several extensions of the pattern in the smallest form are explored. The results offer a new perspective on the proposition of generalised Darwinism that evolutionary phenomena in different domains can be viewed as identical in their basic structure if they are analysed at a sufficiently abstract level of analysis.

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DOI 10.1007/978-3-319-43802-3_6

6.1 Introduction

Darwin defined evolution as: ‘descent with modification, through variation and natural selection’ (Darwin 1876). Even though many people presume that Darwinian evolution is a biological phenomenon, the causal factors of Darwinian evolution can be phrased without referring to organisms in the following way: structural differences between objects (variation), structure-related differences in the capacity to produce next generation objects (in biological terms: reproduction and selection) and the passing on of properties to next generation objects (in biological terms: inheritance). As such properties are not limited to organisms, people have searched for a more general interpretation of Darwin’s concepts, under the name of generalised Darwinism (e.g., Hodgson and Knudsen 2006; Buenstorf 2006; Aldrich et al. 2008; Levit et al. 2011; Stoelhorst 2008). Buenstorf (2006) summarised ideas of Hull (1988) and Dennett (1995) to conclude that the proposition of generalised Darwinism is that ‘at a sufficiently abstract level of analysis, evolution processes in different domains are identical in their basic structure’. Recently, Reydon and Scholz (2014) have analysed this tenet of generalised Darwinism (in short: GD) concluding that ‘biological evolutionary theory sets ontological criteria that GD fails to meet’. The reason for such failure, as we see it, is that the entities that are seen as similar at an abstract level in generalised Darwinism, such as organisms, companies and populations, are not of the same ontological kind. Using the Operator Theory, organisms can be classified as operators, and as countable units, while companies and populations are logical groupings of operators.

This chapter aims at contributing to discussions about generalising Darwinism by suggesting a logic that connects the object-based graph-pattern of Darwinian evolution at the smallest scale with several other approaches. The structure of the smallest scale model was discussed in Sect. 4.4. This smallest model will be used in this chapter as a basis for developing a selection of generalisations and extensions. The advantage of using a smallest scale model as a reference is that elaborations and extensions can always be related to this Darwinian core model. Through the use of a smallest scale model as a reference it is also possible to preclude that high level abstractions that represent evolution *sensu lato*, and that do not comply with the criteria for Darwinian evolution, will be viewed as Darwinian evolution. The aim of this way of working from the bottom up is to avoid logical difficulties that, as has been indicated by Reydon (lecture in Nijmegen 11 February 2016), may emerge if one interprets generalisation as the integration of evolutionary models of, e.g., oak trees, fruit flies and bacteria into an abstract approach in biology, and subsequently applies this abstract biological approach to economy and other sciences. Instead, the pathway that we envision here aims at using the general graph-pattern of Darwinian evolution as a basis in any discipline, such that in biology entities can be identified that comply with this pattern, e.g., oak trees, fruit flies and bacteria, while also in economy and sociology entities can be identified that comply with this pattern.

Attempts at generalising and extending Darwinian evolution have a long history. In biology, the Modern Evolutionary Synthesis and its further development have integrated genetics into evolutionary theory (e.g., Huxley 1942; Maynard Smith

1975; Mayr 1980; Mayr and Provine 1980; Bell 1997; Stearns 2013). In different ways, quantitative aspects of Darwinian evolution at the population level are dealt with by the integrative approaches of, e.g., Price (1970) and by the frameworks of Frank (1997) and Witting (1997, 2008). The Extended Synthesis (Pigliucci and Müller 2010; Laland et al. 2015) has offered a structured overview of relationships with novel developments, such as epigenetics (Jablonka and Lamb 2005), niche construction theory (e.g., Odling-Smee et al. 2003) and horizontal DNA transfer (Danchin et al. 2011; Syvanen 2012). Levels of selection were discussed, e.g., by Lewontin (1970) and Okasha (2006) and Lloyd (2012). An approach based on Darwinian populations has been introduced by Godfrey-Smith (2009). Various broad perspectives have been published that view evolution as a substrate-independent algorithm or that aim at a generalised Darwinism (e.g., Popper 1972; Campbell 1960; Dawkins 1983; Ridley 1985; Endler 1986; Salthe 1993; Plotkin 1994; Dennett 1995; Edlinger 1995; Cziko 1995; Heylighen 1999; Buskes 2013; Losos 2013). Different perspectives on transitions in evolution have been explored in the works of Bickhard and Campbell (2003), Szathmáry and Maynard Smith (1995), Jagers op Akkerhuis and van Straalen (1999), Jagers op Akkerhuis (2010a) and Szathmáry (2015). Furthermore, integrative developments in evolution theory can be found in technology (Brian Arthur and Polak 2006; Brian Arthur 2009), in economy (Hodgson and Knudsen 2006; Beinhocker 2006; Piepenbrock 2009; Stoelhorst 2010) and in sociology (Boyd and Richerson 1985; Depew and Weber 2013; Hannon and Lewens 2013; Buskes 2015).

6.1.1 *Goal and Outline of This Chapter*

The aim of this chapter is to contribute to the generalisation of Darwinism through the use of a model of Darwinian evolution at the smallest scale as a foundation for extensions and elaborations. As it offers a basis for the reasoning in this chapter, we start with a summary of the smallest scale model for Darwinian evolution before discussing seven practical examples that demonstrate how the graph-pattern of Darwinian evolution at the smallest scale can be elaborated. We end with a listing of the results of this chapter.

6.2 Elaborations of Darwinian Evolution at the Smallest Scale

6.2.1 *Darwinian Evolution at the Smallest Scale*

In Chap. 4 of this book Darwinian evolution was defined conceptually by means of an object-based graph. Graph theory makes it possible to simultaneously focus on the kinds of objects, the relationships between the objects and the overall

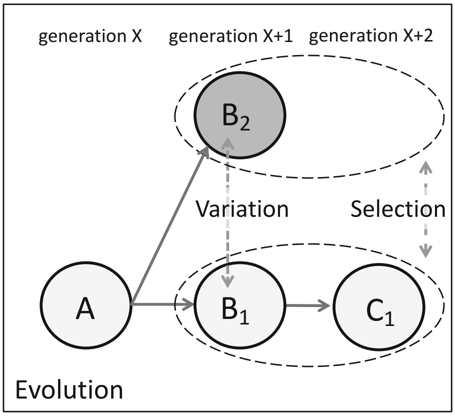

Fig. 6.1 The graph-pattern of Darwinian evolution at the smallest scale (adapted according to footnote in Chap. 5.1). See the text and Fig. 4.4 for explanation

graph-pattern representing Darwinian evolution. It was concluded that the graph-pattern of Darwinian evolution combines a process (derivation) and evaluations (variation and selection), and that, for this reason, the definition of Darwinian evolution refers to more than 'just' a process, but must be viewed as a mixed graph-pattern.

The smallest scale graph pattern that defines Darwinian evolution is shown in Fig. 6.1. In the graph, one finds an object (A), which is viewed as the original. Original A may have been formed de novo, or may be a descendant of an earlier object. From A two objects are derived: B_1 and B_2. Only from B_1 a next generation object C_1 is derived. The objects A, B and C are similar in a major kind (as discussed in Sects. 4.3.2 and 4.3.5) that complies with the specific kind of derivation involved. B_1 and B_2 differ in the absence or presence of a single property. As it represents the least complex model for selection, the pattern of selection is based on the binary measure of the presence or absence of derivation before disintegration. And because it makes use of descent, and generations, the graph-pattern of Darwinian evolution necessarily includes the aspect of time. The graph of Darwinian evolution at the smallest scale should not be mistaken for a biological approach. The biological version is a special case where every object is an organism.

6.2.2 *Patterns of Darwinian Evolution Based on Multiple Generations*

In the smallest scale graph-pattern of Darwinian evolution (Fig. 6.1), variation and selection co-occur in the first generation. More complicated graph-patterns can be imagined, in which variation and selection occur in separate generations. For analysing such new patterns we introduce a new tool, named the window of descent (Fig. 6.2). Figure 6.2 describes four different windows of descent: A, B, C and D. In the windows A, B and C the criteria for Darwinian evolution are not met in one

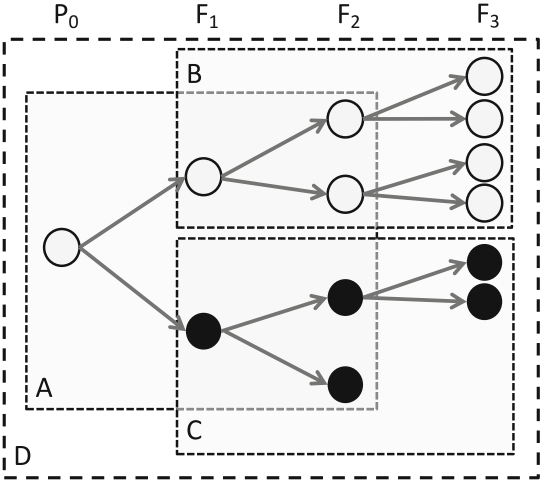

Fig. 6.2 Windows of descent. The main window (*D*) is composed of three smaller windows (*A*, *B* and *C*). *White* and *Black dots* represent objects of the kind white and black, respectively. Columns P_0 to F_3 represent subsequent generations. An *arrow* represents derivation. *No arrow* means no derivation. Only window *D* complies with the extended pattern of Darwinian evolution

generation because variation and selection, based on failure of derivation before disintegration, do not co-occur inside the window. Window D, however, is large enough to bring variation and selection together. Using differently sized windows of descent as a tool, any large genealogy can in principle be broken down. If, for example, variation occurs in generation 2, and selection occurs in generation 15, one may choose a window of descent with a span of 15 generations and in this way assure that the extended pattern of Darwinian evolution is captured inside the window.

6.2.3 *A Developmental History Can Add New Kinds of Organisation*

When an object develops through different kinds of organisation, we will not use the term life history. The reason for this is that the development may include steps that do not represent organism, and hence do not represent life (the concept of life will be defined in Chap. 12). Instead, we will use the term developmental history.

To describe the Darwinian evolution of developmental histories, it must be possible to replace each node in the least complex graph by a developmental history. For making development possible, an object must contain the full *set of developmental rules*, which in interaction with the structures and physiology of the developing organism, and in interaction with environmental factors, can produce a series of changes in the physical construction of the object that together represent the object's developmental history (Fig. 6.3) (e.g., Michod et al. 2006; Reznick 2013). If one wants to describe a developmental history by means of a series of discrete, generally applicable stadia, rather than through a gradual, species specific development, a suitable ontology is needed. In this context, we suggest that it is practical to make use of the Operator Theory, because its classification can be used both as a ranking

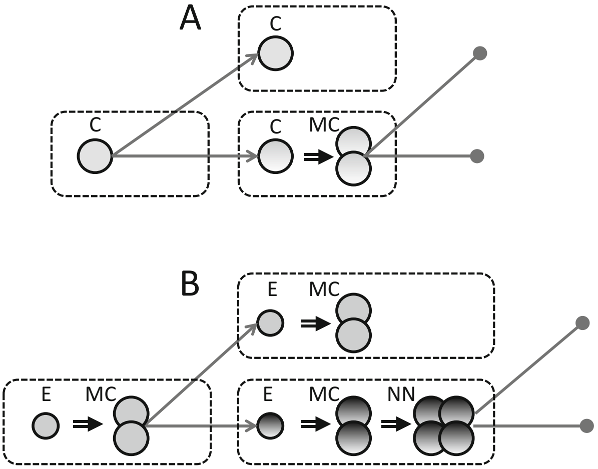

Fig. 6.3 Two examples of how the graph-pattern of Darwinian evolution at the smallest scale can be extended. The original nodes are exchanged by *dashed boxes* that contain a developmental history for an asexual species. (**a**) A graph-pattern of Darwinian evolution for the development towards a multicellular organism, which here proves the fittest option. (**b**) A graph-pattern of Darwinian evolution with development leadig to a neural network organism, which here proves the fittest option. *Solid arrow*: derivation. *A solid line with dot* is a symbol that represents derivation plus the next generation object. *Black double arrow*: between operator kind transition as part of a developmental history. *E* egg cell, *C unicellular organism (cell), MC* multicellular organism, *NN* neural network organism

of kinds of organisms, e.g., unicellular organisms, multicellular organisms, etc. (see Jagers op Akkerhuis 2008, 2010b, 2012b), and as a classification of major kinds of organisation that occur during development, e.g., the unicellular stage, the multicellular stage and the neural network stage. When desired, the classification of stages according to the Operator Theory can be combined with various other classifications, such as larva, instar, pupae, juvenile, etc.

Following the above explanation, we can substitute every node in the least complex graph (Fig. 6.1) with a developmental history. In addition, Fig. 6.3 also illustrates the use of the Operator Theory for the classification of different stages in a developmental history. What is depicted in Fig. 6.3 is a simplified summary of many generations with small changes that finally lead to the two different developmental histories that produce a different kind of operator. The figure focuses on the divergence between two developmental histories, each being represented as a single node in the graph (dashed boxes). In reality, the different developmental histories are the outcome of many small preparatory evolutionary steps. To understand why the many small steps lead to the divergence in kinds, one can invoke a broad range of causes, such as the driving force of autocatalysis (Pross 2005; Jagers op Akkerhuis 2012a), density-dependent competitive interactions (e.g., Witting 1997) and synergism (Corning and Szathmáry 2015).

The structure of Fig. 6.3 can also be used for analysing the construction steps in the developmental history of an object that is not an organism, such as a virus particle. In its least complex form, the developmental history of a virus involves the copying by the cell of a bare strand of DNA/RNA. Such strands are called viroids. A more complicated version of the developmental history emerges when the virus induces the cell to synthesise proteins that will encapsulate the DNA/RNA of the viroid as a protective layer. This layer is named a capsid. And an additional step can be added to the developmental history when a virus with capsid is surrounded by a layer of membrane material that is obtained from the cell upon the export of the virus from the cell. Steps like these can take different forms, and can be viewed as an addition to the developmental history of a virus. Because the virus induces the cell to carry out processes that add next phases to the developmental history of the virus, we speak of a scaffolded developmental history.

6.2.4 Sexual Reproduction

The object-based graph-pattern of Darwinian evolution at its smallest scale is based on objects which through derivation produce next generation objects. This basic model can be extended by allowing for changes during/after derivation as the result of the uptake of DNA from the environment. Uptake of DNA directly from the environment has been observed, for example, in radiolarians (Hespeels et al. 2015). And the uptake of DNA from the environment can also be mediated by viruses in a process called transduction that was discovered in 1951 by Zinder and Lederberg (1952).

In addition, DNA from the environment can also be taken up from another organism. An example of such uptake can be found in bacteria. Bacteria can involve in conjugation, during which two cells are joined through a plasma connection and plasmid DNA is transferred from one bacterium to the other.

Both the uptake of DNA from the environment by radiolarians and the exchange of plasmid DNA during bacterial conjugation are processes that may occur in a specific generation, and that do not have to happen every generation. Similarly, there are many multicellular organisms which reproduce without sexual reproduction, such as asexually reproducing clones of lizards, of insects, etc. In other species of multicellular organism, for example in some nematodes, sexual reproduction may occur in some generations but not in every generation. Finally, there is a large group of multicellular organisms for which reproduction depends obligatorily on the recombination of gametes that have different genders. Such species are said to reproduce sexually.

To show how the pattern of Darwinian evolution at the smallest scale can be extended to account for sexual reproduction, we elaborated in Fig. 6.4 the example of a multicellular endosymbiont organism such as a plant, which classically is referred to as an eukaryote multicellular. The example assumes that the ovum contains the endosymbionts, such as mitochondria and/or chloroplasts, and contains one set of chromosomes. The semen can be viewed as a vehicle for transporting the

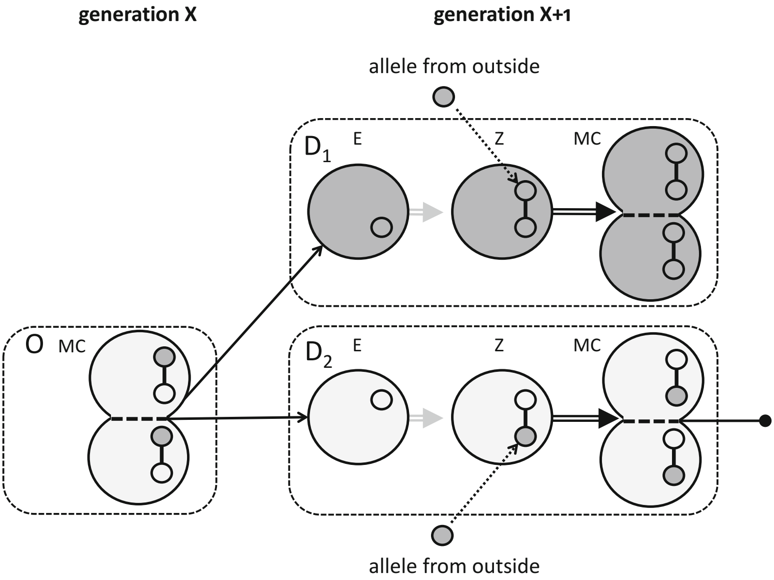

Fig. 6.4 Darwinian evolution at the smallest scale for a sexually reproducing multicellular organism. *Dashed boxes represent a life history as a node in the graph. Large circles* represent organisms, *small circles* represent alleles. The *dark grey allele* is a recessive property that blocks derivation when in a homozygous state (*dark grey organism*). *Dashed boxes* contain all stages of an organism's developmental history. A *solid black arrow* indicates derivation. A *solid black line with a dot* symbolises derivation plus a next generation object. *Open arrows* indicate changes from one developmental history stage to the next (*light arrow* = same operator kind, *black arrow* = new operator kind). *Fine dashed arrows* indicate the incorporation of external DNA. *E* ovum, *Z* zygote, *MC* multicellular. *O* = original. *D1* and *D2* = derived organisms

complementary set of chromosomesto the ovum. When the ovum and the semen fuse this leads to a transition to a so called zygote, after which the developmental history continues towards the multicellular. As the zygote has two sets of chromosomes, one from the ovum and one from the semen, it is said to be diploid. The example in Fig. 6.4 demonstrates how the recombination of chromosomes works in a diploid organism when one or both chromosomes have a recessive allele that causes a homozygous individual to either die or to become infertile. Due to sex, the chance that an offspring organism will contain the deleterious gene, does no longer depend solely on the parent or on mutations, but has also become dependent on the chance that the deleterious allele is obtained via mating. The chance that this happens depends on the relative abundance of individuals that carry the deleterious DNA, that live in the vicinity of the organism, and that are willing to mate.

While Fig. 6.4 focuses on the acquisition of DNA from a random individual in the vicinity, no assumptions are made about whether or not the organism that the individual mates with is of the same species. In fact, mating between organisms of different species occurs quite frequently, as the following well-known examples demonstrate: (1) if a tiger male and lion female, or lion male and tiger female mate, the offspring are tigons, or ligers respectively, (2) If a donkey jack and horse mare, or a horse stallion and donkey jenny mare mate, the offspring are mules or hinnies, respectively. All these mating events lead to infertile offspring, such that after the offspring have reached adulthood the pathways in Fig. 6.4 will all show dead ends, and the overall graphs will represent avolution, as was explained in Sect. 4.5.

6.2.5 From an Object-Based to a Kind-Based Graph-Pattern of Evolution

In the preceding chapters, Darwinian evolution has been discussed as a graph-pattern that is based on objects. Here, it will be explored whether the same graph-pattern can also be used for a more abstract representation in which nodes that represent actual objects are replaced by nodes that represent a group of objects which are all of the same kind, such that the kind is uniform. The generality of a kind-based approach is explored in Fig. 6.5, which shows a Darwinian graph-pattern in which different kinds of atoms are formed, some of which may form the basis of dual closure. Now the nodes do not represent objects, but groups of objects, and the derivation process is not reflecting a particular interaction, but a particular series of interactions that occur at the level of nuclear fusion.

Originally, the universe contained predominantly hydrogen atoms. Later, a cascade of nuclear fusion reactions (in stars) produced atoms of various new kinds, such as helium, potassium, carbon, uranium, etc. Fusion reactions result in a reduction of the number of actual objects. For this reason the event does not classify as a derivation process, given the definition used so far. The reason is that derivation is assumed to cause an increase in the number of objects. Instead, a fusion reaction can be viewed as a combinatory process. To now create a Darwinian graph-pattern for the transition from atoms to molecules, it is suggested to analyse the fusion process at a higher level, such that it can cause the graph-pattern of variation. This is pos-

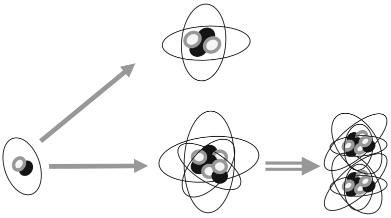

Fig. 6.5 An elaboration of the graph-pattern of Darwinian evolution using objects ofuniform kinds as the nodes. In part A the nodes represent atoms and molecules. In part B the nodes represent molecules and cells. *Solid arrow*: meta-level derivation. *Open arrow*: dual closure. *No arrow*: no dual closure

sible if the cascades of fusion reactions that lead to increasingly complex atoms are re-interpreted as an abstract meta-process through which different *kinds* of atoms are formed. Now that the analysis no longer involves concrete objects and their physical interactions, but uniform kinds of specific objects, the pattern of variation can be rephrased in terms of atoms of different (sub) kinds, such as helium atoms, or lithium atoms. Such an adaptation allows for a new graph-pattern in which each node represents all the atoms of a specific (sub) kind.

To complete the graph-pattern of evolution, one needs atoms of various kinds as the basis for selection. But while in biology the graph-pattern of selection is based on the failure of derivation, derivation in the sense of reproduction is not something that atoms can do. How can the concept of failure of derivation be linked to atoms? To answer the latter question, we suggest extending the concept of selection in such a way that in addition to the failure of derivation also the failure of the production of a next kind of dual closure (FOC) is accepted as a criterion for the pattern of selection. Fig. 6.5 illustrates the transition from atoms to molecules. Here the relevant dual closure is associated with the formation of covalent bonds. Covalent bonds are formed by atoms which have unpaired electrons in their outer shells. For example in carbon, nitrogen and oxygen an incomplete pair of electrons leads to the pairing of electrons of two atoms which after pair formation move between the atoms in a common electron orbit. In other kinds of atoms, e.g., helium and argon, the presence of paired electrons in all electron shells blocks the formation of covalent bonds.

The above demonstrates that one can re-interpret the graph-pattern of Darwinian evolution in terms of uniform kinds, if one extends the concepts of variation and selection to the abstract level of uniform kinds and focuses on dual closure as the selection criterion. The resulting generalisation can be applied to all the transitions in the operator hierarchy. For example, in biology a cascade of derivation processes may lead from an original kind of bacterium to different new bacteria. Of all the different bacteria some may be capable of developing to unicellular endosymbionts. Now, a new uniform kind has emerged that can be used as a node in the above extension of the pattern of Darwinian evolution at the smallest scale. If this logic is applied, a sequence of graphs of extended patterns of Darwinian evolution can be used to describe the emergence of increasingly complicated operators.

If one uses kinds as nodes, one has to be cautious that all the objects represented by the kind comply without exception with the criteria for the kind. This has important consequences if one would try to use a sexual species as a kind. To demonstrate that all individuals belong to the same sexual species, and in this way are of the same kind, one can (among other criteria) use the criterion that every member can in principle mate with all the other members of the opposite sex in the group, when having reached the appropriate age, and that such mating will result in fertile offspring (e.g., Hennig 1966; Reydon 2005). While in theory it may be possible to test this criterion, in practice it will hardly ever be possible to obtain such a proof. Moreover, ring-species do not comply with the criteria of a uniform class, and never will, because while individuals that live in each-other's vicinity can mate, individuals at distant edges of the geographical distribution of the population cannot. This implies that it is not possible for all individuals to mate, not even in theory. This problem that there can always be individuals of the species that will fail to mate, represents a serious obstacle if one aims at representing the nodes in a graph of evolution by species as uniform kinds. If one views the abstract concept of a species as an object that can show generations, variation and selection this leads to philosophical problems, as has also been discussed by, e.g., Reydon (2005), Wilkins (2009) and Reydon and Scholz (2014).

6.2.6 Thoughts as Nodes in the Pattern of Darwinian Evolution

Despite modern techniques, it is not yet fully known what happens in the brain when perceptions are stored and memories are processed. Yet, also without such knowledge it can be analysed phenomenologically how a process of thinking can lead to a pattern of Darwinian evolution based on the memorisation of concepts. The reasoning we will present runs parallel to the analyses of evolutionary problem solving by Popper (1972).

A concept is viewed here as a memory that can be addressed individually, either as a unity, e.g., the concept of a tree, or as a continuity, e.g., the concepts of time and infinity. A concept is viewed as the basic building block of thinking. Through modification and combination an original concept can form the basis for a range of alternatives. Such alternative concepts, as well as the pathways to their formation, can be memorised. If a person now has a mental goal, for example the solving of a specific problem, multiple solutions can be created for dealing with the problem at hand. Subsequently, this range of concepts can be filtered in relation to their contribution to the goal. The concepts that represent desirable solutions can be chosen as the basis for further rounds of problem solving. As several alternative concepts can be derived, while some of these are chosen, and others are rejected, the result complies with the pattern of Darwinian evolution.

6.2.7 Feedback and Niche Construction

The object-based graph-pattern of Darwinian evolution implicitly includes feedback. Using organisms as an example, this feedback takes the following form. The interplay between genetic properties and environmental condition causes phenotypes which differ in their capacity to realise derivation. The environmental conditions may change autonomously and/or may additionally be influenced by the activities of the organisms, for example through the construction of a beaver dam, a termite hill, or through the transformation of a forested area to a grassy area as the result of grazing activity of large herbivores. The better organisms fit to the environment they live in and/or co-create, the higher their chances ofsurvival. In a group of organisms, the mortality of the individuals that do not fit will affect the overall genetic composition of the remaining individuals (Jones et al. 1994; Odling-Smee et al. 2003), and therewith set the basis for a new interplay between genetic properties and environmental conditions. This example shows that while the object-based graph-pattern of Darwinian evolution does not include feedback in an explicit way, the feedback is implicitly included, as the cause of the pattern of selection. Meanwhile, the capacity of eu-socially dwelling colonial individuals to construct a suitable living environment, such as an ant hill, bee hive, etc., may strongly affect their survival, which from an evolutionary perspective is especially relevant for the colony's queen.

6.2.8 Nested Darwinian Evolution

When analysing nested patterns of Darwinian evolution, the Operator Theory uses the operator as the preferred focal level. Accordingly, nested evolution represents a phenomenon inside an operator. As an example one can focus on a protozoon which hosts a number of mitochondria. When the mitochondria reproduce inside the protozoa, and the offspring mitochondria differ in properties and in their success of realising derivation, the mitochondria can take the position of nodes in the graph and for this reason may comply with the pattern of Darwinian evolution. Meanwhile, when the protozoa splits to produce two offspring the different mitochondria may become randomly distributed over the pair of newcells. In this way, mitochondrial evolution contributes to differences between offspring protozoa. And the offspring protozoa can be viewed as the nodes of a graph, which potentially complies with the pattern of Darwinian evolution. Inside the mitochondria, parts of the DNA such as transposonsmay multiply, during which mutations may occur. While some transposonsmay disintegrate a graph-pattern may emerge that complies with a pattern of Darwinian evolution. When all these patterns occur, the pattern of Darwinian evolution of the transposons becomes part of the pattern of Darwinian evolution of the mitochondria, which becomes part of the pattern of Darwinian evolution of the protozoa.

It is emphasised that the Operator Theory only views as nested evolution any Darwinian pattern which occurs inside an object which, like an organism, can itself act as the basis for a pattern of Darwinian evolution. An interaction system based on organisms, such as a population, does not comply with this viewpoint. The reason is that an interaction system is viewed as a conceptual entity (see Sect. 2.7.3), not as a physical entity, and that when entities that belong to the group (the organisms) produce the pattern of evolution, this does represent evolution, but not in a nested way. In contrast to an operator, which due to the presence of dual closure can be viewed in a strict way as a single countable object, an interaction system is viewed as an emergent consequence, a meta-phenomenon that emerges from the behaviours of the contributing individuals without producing a new operator.

Meanwhile, the *behaviour* of the individuals may evolve according to the Darwinian pattern, when it is based on genetic coding, that is selected for over many generations, such as the reflexes involved in the formation of a school of fish, and/or when in the minds of an organism learned/invented behaviour evolves according to the Darwinian pattern.

6.3 Discussion

The current chapter focused on generalised Darwinism and its proposition that evolution processes in different domains can be viewed as identical in their basic structure if they are analysed at a sufficiently abstract level of analysis. The results of the current analyses indicate that questions can be raised about such a proposition. Firstly, there is a disjunction between the concepts of evolution *sensu lato*, which refers to any and all processes of unrolling, and patterns of Darwinian evolution, that combine processes, notably reproduction/derivation, and evaluations, such as the patterns of variation and selection. As it is based on the combination of processes and evaluations, Darwinian evolution does not represent 'just' a process.

Secondly, there is a disjunction between the models that are part of the family of Darwinian graph-patterns, and the models that analyse evolution at the meta-level of population parameters. Population-based approaches abstract away from the basic graph-pattern of Darwinian evolution by aggregating over all the relationships between parents and offspring, as well as by aggregating over different kinds of graph-patterns. This suggests that models at higher levels of abstraction will not always relate to a uniform kind of underlying patterns. These special properties of population-based averages limit the possibilities of generalising evolutionary thought, and in particularly the possibilities of generalising Darwinism.

While aiming at moving away from such limitations, the current chapter has opened up various ways in which Darwinism can be extended and generalised in a structured way.

6.3.1 A Family of Darwinian Patterns

The model of Darwinian evolution at the smallest scale can offer a logical basis for extensions and elaborations and in this way lead to a range of more complex models. It is important that, through a process of simplification and representation the objects and/or relationships of a complex model can always be scaled down to the model at the smallest scale. For example, if one starts with a graph-pattern based on developmental histories (see Fig. 6.4) and one reduces every developmental history in the graph to an object, one re-creates the object-based graph-pattern of Darwinian evolution at the smallest scale. When applied this way, a central, minimal model is relevant for the fields of Darwinian Theory and generalised Darwinism, because it enables one to view any and all graph-patterns that can be linked to the pattern at the smallest scale (and only such patterns) as representing Darwinian evolution. The linking of variations to a smallest scale model offers a structured methodology for defining different kinds of Darwinian evolution, and indicates new pathways for refuting suggestions that 'attempts to define evolution in some narrower and sharper sense, whether Darwinian or otherwise, are unlikely to make much headway' (Hodgson and Knudsen 2006).

6.3.2 Object-Based Graphs of Population-Based Models of Darwinian Evolution

In close correlation with the population-based viewpoint of the Modern Synthesis, the evolutionary literature offers many object-based graphs that illustrate the population viewpoint (e.g., Godfrey-Smith 2009). Such graphs typically connect a large number of dots in a box which represent the parental population, and a large number of dots in a box which represent the offspring population (Fig. 6.6). Lines, representing descent, are drawn between parents and offspring. When focusing on fractions of properties in populations the calculations focus on population-based averages/fractions and the connections between parents and offspring are lost. In other words, because it sums several underlying evolution patterns, the population-based approach focuses on evolution as a meta-phenomenon. If one defines the concept of Darwinian evolution by means of a graph pattern, however, population averages are no longer sufficient, because all parent-offspring relationships must be respected. The use of an object-based approach thus implies that population-based

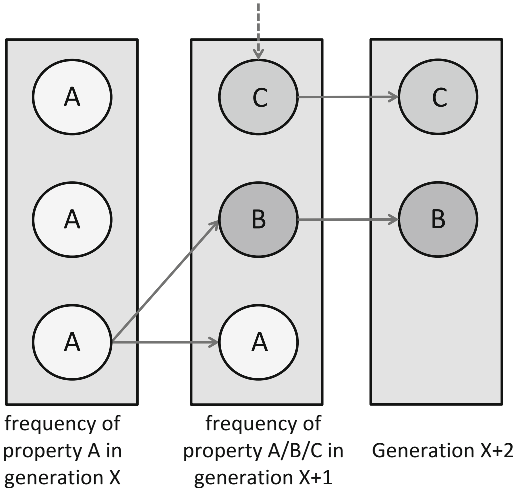

Fig. 6.6 Population-based graph of how individuals in generation *X* contribute to offspring in generation *X* + 1. The example is based on asexual reproduction. Organisms A, B and C have different DNA structures. B has a mutation. C is an immigrant. *Grey boxes* represent populations at generation *X* to *X* + 2. *Arrow* = derivation. *Dashed arrow* = immigration

averages must be split again into object-based patterns of reproduction. Thus, while the population viewpoint uses averages and fractions for calculating overall *effects* of evolution, the individual-based definition of Darwinian evolution focuses on how relationships between a specific parent and its offspring define different *kinds* of graph-patterns, some of which represent Darwinian evolution while others do not.

6.3.3 Generalised Darwinism and Cultural Evolution

The ideas about generalisation of Darwinian evolution which are offered in the current chapter also contribute to the question of '… how far the analogy between culture and genetic evolution should be pushed' (Acerbi and Mesoudi 2015) when 'Cultural evolution studies are characterised by the notion that culture evolves according to broadly Darwinian principles'. While being inspired by existing population genetic tools, Cavalli-Sforza and Feldman (1981) and Boyd and Richerson (1985) constructed dual inheritance models for cultural evolution, which account for genetic as well as behavioural aspects. Such population models have similar advantages as population-based genetic models when it comes to the quantification of the *outcome* of evolutionary processes. The current chapter now contributes to the field by offering a basis for a *conceptual* definition of Darwinian aspects underlying cultural evolution. The idea is that by using object-based graph-patterns for Darwinian evolution one can specify the statement that 'culture evolves according to *broadly* Darwinian principles' (Acerbi and Mesoudi 2015).

The object-based perspective on the pattern of Darwinian evolution implies that one cannot speak about the Darwinian evolution of behavioural groups, such as companies. The reason is that objects are of a different logical kind than behavioural groups, a difference which was indicated by Reydon and Scholz 2014, and was explained in detail in Sect. 2.7.3. While some authors speak in a general way about the evolution of behavioural groups, an object-based approach implies that one must view any behavioural group as the product of the behaviour of individuals. Here, the example of a bee hive can serve as an example. The hive can be viewed as a social construction that emerges as the result of the behavioural interactions of the bees. The larger part of the behaviour of a bee depends on how the genes of the queen and consort code for the neural network structure of the bee, and on how this neural network causes behavioural reflexes. Similarly, a soccer team and a company can be viewed as a behavioural group that results from social interactions between humans. If a behavioural group changes over time, such changes can be discussed in a general way as evolution, by referring to the Latin origin evolvere, which means to unroll. However, as soon as one refers to *Darwinian* evolution in the sense of an individual-based graph-pattern (Chap. 4) one necessarily must make use of objects as the basis for analysing the evolution of behavioural group structure. And in the case of group behaviour, one can focus on how the DNA codes for behaviour based on reflexes, or on how some animals learn how to behave in a group. When talking about learning, the focus shifts towards the ideas an entity carries in his/her mind about his/her participation in the behavioural group. An entity's ideas about such participation may change, and the effect hereof will be that its contribution to a behavioural group changes, and that finally the behavioural group, as a meta-phenomenon, changes. In Sect. 6.2.6 we discussed that changes in the brain of a person about his/her participation in a behavioural group can, like any other idea, comply with the pattern of Darwinian evolution.

6.3.4 Statements About Darwinian Evolution

The results of this chapter illustrate that the object-based graph-pattern of Darwinian evolution at the smallest scale can be used as a foundation for extrapolations and extensions which together create a family of patterns of Darwinian evolution. In turn, the different patterns in this family of Darwinian patterns can be used as building blocks that can be integrated to create larger patterns that, as meta-phenomena, are studied in terms of societal groups, companies and culture. In this way, complex constellations of interconnected smaller evolutionary patterns can scaffold the future bridging of the gap between Darwinian evolution and social change.

The existence of a family of patterns of Darwinian evolution is a new idea that may still profit from further discussion. In the meantime, it can be used as a theoretical tool that allows a person to distinguish between phenomena that do and phenomena that do not represent evolution. As far as we know, a stringent tool for distinguishing between graph-patterns of Darwinian evolution and other phenomena is new, and may offer new perspectives on the resolution of conceptual ambiguity. In addition to the possibility of indicating whether or not a phenomenon represents Darwinian evolution, it is also interesting to examine statements about Darwinian evolution, and how these may have to be looked at in a new way now that we defined Darwinian evolution by means of a graph-pattern.

First of all, the graph-pattern of Darwinian evolution demands more than just change, because there are many patterns of change which do not comply with the pattern of Darwinian evolution. Accordingly, a definition that is based on a graph-pattern implies that there is a difference in the kind of phenomenon between evolution *sensu lato*, and Darwinian evolution.

Secondly, when defining Darwinian evolution as a graph-pattern the concept can no longer be viewed as a process. This may seem a counterintuitive conclusion. This conclusion was arrived at by the observation that the graph-pattern of Darwinian evolution on the one hand includes processes involved in the production of next generation objects and on the other hand includes the pattern of selection. As has been discussed in Sect. 4.3.5 the pattern of selection can be classified as an evaluative pattern, and that for this reason the overall graph-pattern of Darwinian evolution can no longer be viewed as a process.

Thirdly, a graph-pattern of Darwinian evolution does not represent a fact. Instead we view a pattern of evolution as an *agreement*. Such an agreement can involve the least complicated pattern of evolution, or a member of the family of related patterns.

Which members can be part of this family is still open to investigation and debate. The graph-pattern of evolution being the result of an agreement, it makes little sense to try to prove that this agreement is correct or incorrect. However, it can be analysed, and potentially be falsified, whether or not a specific pattern of evolution complies with the criteria that were deemed relevant for its construction. And once there is agreement about whether or not a specific graph-pattern represents Darwinian evolution, it will actually become very easy to prove (through one-to-one correspondence) the existence in the physical world of objects and relationships that comply with this pattern.

Fourthly, if one views Darwinian evolution as a pattern, this changes the perspective on what can be viewed as a theory of evolution. Of course, one can have thoughts about different patterns of evolution, or demonstrate that a given pattern can be found in real-world situations. But these things have little to do with a theory of evolution. Instead, we suggest that one may theorise about basic mechanisms that can cause the emergence of a specific graph-pattern of evolution. Such a theory would rekindle the thinking about mechanisms by demanding a focus on thermodynamics, self-organisation processes, feedback loops, niche construction (Odling-Smee et al. 2003), etc. Based on theories about mechanisms it may be possible to model and predict the probability that, over generations of newly formed entities, the processes involved lead to the occurrence of a graph-pattern of Darwinian evolution, compared to the chances that other graph-patterns occur.

Fifthly, Darwinian evolution is not a law. A law is deduced from observation, and describes a particular natural phenomenon that always occurs if specific conditions are present. However, in a stochastic environment, the same processes that lead to a pattern of Darwinian evolution can also lead to other patterns. Accordingly, the graph-pattern of Darwinian evolution is only one of various possible results of the processes involved. The occurrence of Darwinian evolution, therefore, is not a law but a probabilistic result. On the other hand, a pattern of Darwinian evolution may be a lawful result of the dynamics in a specific system. For example, if we use the multigenerational extension of the least complicated pattern of Darwinian evolution, the probability that the pattern of Darwinian evolution is realised increases with the number of generations if a system has the following properties: the entities show multiplication, every second generation entity may possess one or more structural properties which differ from the parent, some of these properties are causally linked to the probability that an entity realises replication, and, there are limits to the number of entities in the system and/or to the amount of resources they can use such that at a specific moment some entities will die before multiplication. It is almost certain that, given long enough time, a pattern of Darwinian evolution will be realised in such a system.

Sixthly, the pattern of Darwinian evolution (on the level of individuals) is not a necessary requirement for the formation of species. The reason for this is that mutations that affect the mating choice, but that have no effects on survival or on the number of offspring (they are neutral in this sense), may lead to the separation of groups of individuals without selection (e.g., Magnus 1998).

Seventhly, the pattern of Darwinian evolution does not classify as an algorithm. An algorithm describes a series of activities that are carried out on, or by objects. However, the choice to use a pattern of Darwinian evolution is based on the necessity of analysing, e.g., variation/selection as a pattern, not as an activity. What we aim at here, is that an algorithm can lead to the pattern of Darwinian evolution, or can be used to assess the presence of the pattern of Darwinian evolution. But an algorithm cannot represent a pattern of Darwinian evolution.

Eighthly, the pattern of Darwinian evolution neither represents a recipe. A recipe is based on ingredients and activities, and the same recipe will in principle always lead to the same result. However, even though the processes involved (the recipe) may remain the same, the recipe itself does not represent the pattern of evolution. And every time that the recipe is followed, chance processes will affect the outcome, such that sometimes the recipe results in a pie (a pattern of Darwinian evolution) and sometimes in a different product, or even in no product at all.

Ninthly, it has frequently been stated that a substrate neutral definition of Darwinian evolution may be found. However, the different graph-patterns of Darwinian evolution are neither substrate independent, nor substrate neutral. Although many different entities can fit in with one or more of the patterns of Darwinian evolution, it is not the case that any and all entities can be used in combination with any and all patterns of Darwinian evolution. For example, one of the criteria of the pattern of Darwinian evolution is that at least some entities realise derivation. Due to this criterion, one cannot replace the nodes in the pattern by things that do not have generations, such as species, ecosystems or planets, or stars. The formation of a new star from the debris of one or more exploded stars is not viewed as a derivation event, but as an aggregation event.

Last but not the least, the pattern of Darwinian evolution cannot be viewed as a driving force that is causal to the emergence of new entities. Instead, things work the other way around. There are driving forces in the world that lead to processes, and these processes and their results may match (or fail to match) a specific pattern of Darwinian evolution. Only the combinations of events and results that match with a graph-pattern of Darwinian evolution are viewed as Darwinian evolution according to the current perspective.

6.4 Conclusions

1. A developmental-history can be matched with the graph-pattern of Darwinian evolution if every node in such graph-pattern represents the development through a developmental-history.
2. It is possible to extend a model of Darwinian evolution at the smallest scale to a model in which the patterns of variation and selection occur in different generations.
3. The object-based graph-pattern of Darwinian evolution can be extended to include kinds. After some specific generalisations the use of kinds makes it pos-

sible to view every transition in the operator hierarchy as Darwinian evolution. Through this technique it can be demonstrated that the entire operator hierarchy represents a meta-Darwinian pattern.
4. It was demonstrated that when looking at thoughts in a phenomenological way, thoughts can comply with the pattern of Darwinian evolution.
5. The generalisations and extensions of the object-based graph-pattern for Darwinian evolution at the smallest scale represent a stringent way of generalising Darwinism. Meanwhile, this approach indicates how different models of Darwinian evolution can function as the basis for metal-level phenomena, such as populations, companies, culture, etc. Meanwhile, it will generally be impossible to create a direct match between meta-level phenomena and the Darwinian graph-pattern.

References

Acerbi A, Mesoudi A (2015) If we are all cultural Darwinians what's the fuss about? Larifying recent disagreements in the field of cultural evolution. Biol Philos 30:481–503

Aldrich HE, Hodgson GM, Hull DL, Knudsen T, Mokyr J, Vanberg VJ (2008) In defence of generalized Darwinism. J Evol Econ 18:577–596

Beinhocker ED (2006) The origin of wealth. Evolution, complexity, and the radical remaking of economics. Harvard Business School Press, Boston, MA

Bell G (1997) Selection, the mechanism of evolution. Chapman and Hall, New York

Bickhard MH, Campbell DT (2003) Variations in variation and selection: the ubiquity of the variation-and-selective-retention ratchet in emergent organizational complexity. Found Sci 8:215–282

Boyd R, Richerson PJ (1985) Culture and the evolutionary process. University of Chicago Press, Chicago

Brian Arthur W (2009) The nature of technology. What it is and how it evolves. Penguin, London, England

Brian Arthur W, Polak W (2006) The evolution of technology within a simple computer model. Complexity 11:23–31

Buenstorf G (2006) How useful is generalized Darwinism as a framework to study competition and industrial evolution? J Evol Econ 16:511–527

Buskes C (2013) Darwinism extended: a survey of how the idea of cultural evolution evolved. Philosophia. http://link.springer.com/article/10.1007%2Fs11406-013-9415-8#

Buskes C (2015) Darwinizing culture: pitfalls and promises. Acta Bioteoretica. doi:10.1007/s10441-015-9247-y

Campbell DT (1960) Blind variation and selective retention in creative thought as in other knowledge processes. Psychol Rev 67:380–400

Cavalli-Sforza LL, Feldman MW (1981) Cultural transmission and evolution: a quantitative approach. Princeton University Press, Princeton, NJ

Corning PA, Szathmáry E (2015) "Synergistic selection": a Darwinian frame for the evolution of complexity. J Theor Biol 317:45–58

Cziko G (1995) Without miracles. Universal selection theory and the second Darwinian revolution. MIT Press, Cambridge, MA

Danchin E, Charmantier A, Champagne FA, Mesoudi A, Pujol B, Blanchet S (2011) Beyond DNA: integrating inclusive inheritance into an extended theory of evolution. Nat Genet 12:475–486

Darwin C (1876) On the origin of species by means of natural selection, or he preservation of favoured races in the struggle for life, 6th edn. John Murray, London

Dawkins R (1983) Universal Darwinism. In: Brendall DS (ed) Evolution from molecules to man. Cambridge University Press, Cambridge, pp 403–425

Dennett DC (1995) Darwin's dangerous idea: evolution and the meanings of life. Simon and Schuster, New York

Depew DJ, Weber BH (2013) Challenging Darwinism: expanding, extending, replacing. In: Ruse M (ed) The Cambridge encyclopedia of Darwin and evolutionary thought. Cambridge University Press, Cambridge

Edlinger K (1995) Organismen: Konstructionen oder Gen-Arrangements? Biologisches Zentralblatt 114:160–169

Endler J (1986) Natural selection in the wild. Princeton University Press, Princeton, NJ, 336 pp

Frank SA (1997) The Price equation, Fisher's fundamental theorem, kin selection, and causal analysis. Evolution 51:1712–1729

Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford

Hannon E, Lewens T (2013) Cultural evolution. In: Losos JB, Baum DA, Futuyma DJ, Hoekstra HE, Lenski RE, Moore AJ, Peichel CL, Schluter D, Whitlock MC (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Hennig W (1966) Phylogenetic systematics. University of Illinois Press, Urbana

Hespeels B, Xiang L, Flot J-F, Pigneur L-M, Malaisse J, Da Silva C, Van Doninck K (2015) Against all odds: trehalose-6-phosphate synthase and trehalase genes in the Bdelloid rotifer Adineta vaga were acquired by horizontal gene transfer and are upregulated during desiccation. PLoS One 10:e0131313

Heylighen F (1999) The growth of structural and functional complexity during evolution. In: Heylighen F, Bollen J, Riegler A (eds) The evolution of complexity. Kluwer, Dordrecht, pp 17–44

Hodgson GM, Knudsen T (2006) Why we need a generalized Darwinism, and why generalized Darwinism is not enough. J Econ Behav Organ 61:1–19

Hull DL (1988) Science as a process. An evolutionary account of the social and conceptual development of science. Science and its conceptual foundations. University of Chicago Press, Chicago

Huxley JS (1942) Evolution: the modern synthesis. Harper, New York

Jablonka E, Lamb MJ (2005) Evolution in four dimensions: genetic, epigenetic, behavioral, and symbolic variation in the history of life. MIT Press, Cambridge, MA

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organization of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2010a) The Operator Hierarchy, a chain of closures linking matter life and artificial intelligence. PhD thesis, Radboud University, Nijmegen

Jagers op Akkerhuis GAJM (2010b) Towards a hierarchical definition of life, the organism, and death. Found Sci 15:245–262

Jagers op Akkerhuis GAJM (2012a) The pursuit of complexity. The utility of biodiversity from an evolutionary perspective. KNNV Publisher, Zeist, The Netherlands

Jagers op Akkerhuis GAJM (2012b) The role of logic and insight in the search for a definition of life. J Biomol Struct Dyn 29:619–620

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego-bricks of nature: evolutionary transitions from fermions to neural networks. World Futures 53:329–345

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69:373–386

Laland KN, Uller T, Feldman MW, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J (2015) The extended evolutionary synthesis: its structure, assumptions and predictions. Proc R Soc Biol Sci 2015282 20151019

Levit GS, Hossfeld U, Witt U (2011) Can Darwinism be "Generalized" and of what use would this be? J Evol Econ 21:545–562

Lewontin RC (1970) The units of selection. Annu Rev Ecol Syst 1:1–18

Lloyd E (2012) Units and levels of selection. In: Zalta EN (ed) The Stanford encyclopedia of philosophy. Winter 2012 Edition. http://plato.stanford.edu/archives/win2012/entries/selection-units/

Losos JB (2013) What is evolution? In: Losos JB, Baum DA, Futuyma DJ, Hoekstra HE, Lenski RE, Moore AJ, Peichel CL, Schluter D, Whitlock MC (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Magnus D (1998) Evolution without change in gene frequencies. Biol Philos 13:255–261

Maynard Smith J (1975) The theory of evolution, 3rd edn. Penguin, Harmondsworth

Mayr E (1980) Prologue: Some thoughts on the history of the evolutionary synthesis. In: Mayr E, Provine WB (eds) The evolutionary synthesis: perspectives on the unification of biology. Harvard University Press, Cambridge, MA, 1–48

Mayr E, Provine WB (eds) (1980) The evolutionary synthesis: perspectives on the unification of biology. Harvard University Press, Cambridge, MA

Michod RE, Viossat Y, Solari CA, Hurand M, Nedelcu AM (2006) Life-history evolution and the origin of multicellularity. J Theor Biol 239:257–272

Odling-Smee JF, Laland KN, Feldman MW (2003) Niche construction: the neglected process in evolution, Monographs in population biology 37. Princeton University Press, Princeton, NJ

Okasha S (2006) Evolution and the levels of selection. Oxford University Press, Oxford

Piepenbrock TF (2009) Toward a theory of the evolution of business ecosystems: enterprise architectures, competitive dynamics, firm performance and industrial co-evolution. MIT. http://hdl.handle.net/1721.1/57976

Pigliucci M, Müller GB (2010) Evolution—the extended synthesis. MIT Press, Cambridge, MA

Plotkin HC (1994) Darwin machines and the nature of knowledge: concerning adaptations, instinct and the evolution of intelligence. Harvard University Press, Cambridge, MA

Popper KR (1972) Objective knowledge: an evolutionary approach. Oxford University Press, London

Price GR (1970) Selection and covariance. Nature 227:520–521

Pross A (2005) On the emergence of biological complexity: life as a kinetic state of matter. Origins Life Evol Bios 35:151–166

Reydon T (2005) On the nature of the species problem and the four meanings of 'species'. Stud Hist Philos Biol Biomed Sci 36:135–158

Reydon TAC, Scholz M (2014) Searching for Darwinism in generalized Darwinism. Br J Philos Sci. doi:10.1093/bjps/axt049

Reznick D (2013) Evolution of life histories. In: Losos JB et al (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Ridley M (1985) The problems of evolution. Oxford University Press, Oxford

Salthe SN (1993) Development and evolution: complexity and change in biology. MIT Press, Cambridge, MA

Stearns SC (2013) Natural selection, adaptation, and fitness; an overview. In: Losos JB et al (eds) The Princeton guide to evolution. Princeton University Press, Princeton, NJ

Stoelhorst JW (2008) The explanatory logic and ontological commitments of generalized Darwinism. J Econ Methodol 15:343–363

Stoelhorst JW (2010) The firm as a Darwin machine: how generalized Darwinism can further the development of an evolutionary theory of economic growth. Papers on Economics and Evolution 1019, Max Planck Institute of Economics, Jena

Syvanen M (2012) Evolutionary implications of horizontal gene transfer. Annu Rev Genet 46:341–358

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. Proc Natl Acad Sci U S A 112:10104–10111

Szathmáry E, Maynard Smith J (1995) The major evolutionary transitions. Nature 374:227–232

Wilkins JS (2009) Species: a history of the idea, species and systematics. University of California Press, Berkeley

Witting L (1997) A general theory of evolution by means of selection by density dependent competitive interactions. Peregrine publishers, Arhus

Witting L (2008) Inevitable evolution: back to The Origin and beyond the 20th Century paradigm of contingent evolution by historical natural selection. Biol Rev 83:259–294

Zinder ND, Lederberg J (1952) Genetic exchange in Salmonella. J Bacteriol 64:679–699

Chapter 7
A Critical Assessment of Graph-Based Generalized Darwinism

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Abstract This paper is a brief commentary on the specific proposal advanced by Jagers op Akkerhuis, Spijkerboer, and Koelewijn in the present volume (Chap. 6) on how Darwinian evolutionary theory could be generalized. However, I want to take the opportunity to present a broader criticism of Generalized Darwinism that focuses on what in my view is the fundamental epistemological problem faced by Generalized Darwinism (Sect. 7.1) and the ontological solution that proponents of Generalized Darwinism offer (Sect. 7.2). On the basis of this criticism, I will examine the proposal by Jagers op Akkerhuis and coauthors and argue that while the proposal is a very useful way ahead toward the *formulation* of Generalized Darwinism, that is toward constructing a formalism for Generalized Darwinism into which all cases of Darwinian evolution can be fitted, it is insufficient as an ontological solution to the foundational ontological problem that Generalized Darwinism faces (Sect. 7.3).

7.1 The Epistemological Problem of Generalized Darwinism

Generalized Darwinism is a loosely knit line of work (or research program, if you like) that is slowly establishing itself in interdisciplinary areas of investigation.[1] It is based on the assumption that Darwinian evolution does not only occur in the living world, but can be found in various contexts outside the biological domain too. This is not to say that exactly the same natural process is found in the living world as well as in various domains of the nonliving world. The claim that proponents of Generalized Darwinism make rather is that there is a class of processes—Darwinian evolutionary processes—that occur in different domains and differ among each other in many details, but still share an overall structure such that all processes in the class can be

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[1] See Scholz and Reydon (2013) and in particular Reydon and Scholz (2015) for a broader discussion of what Generalized Darwinism is, and what it is not.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_7

described by the same general account.[2] The idea is that while each such process will require its own fine-grained theoretical description, from a sufficiently coarse-grained view all Darwinian evolutionary processes look the same, irrespective of whether they occur in biological, economic, social, or other contexts.[3]

Generalized Darwinism has to be distinguished from a number of other proposals with respect to applications of Darwinian evolutionary theory outside its original domain of application (i.e., the change of populations of organisms through time due to natural selection). Foremost, Generalized Darwinism as it is developed today must be distinguished from Universal Darwinism as introduced by Richard Dawkins (Dawkins 1983, 2008). Dawkins never envisaged Darwinian evolution to occur in nonbiological systems and even cautioned against getting carried away and seeing Darwinian evolution everywhere (Dawkins 2008; Reydon and Scholz 2015: 565–566). Dawkins' point rather was that there was no reason to think that Darwinian evolution could only occur on planet Earth and that Darwinian evolution could in principle occur in all *living* systems anywhere in the universe. Oversimplifying this is to say that if at some point we find extra-terrestrial life, we can be comparatively certain that it will evolve in largely the same way as life on Earth evolves.

The contrast between Generalized Darwinism and Universal Darwinism is important, because it highlights a crucial epistemological issue that both approaches aim to address, namely the question of the scope of Darwinian evolutionary theory and Darwinian evolutionary models. We are quite familiar with Darwinian evolution, because we have studied it in a variety of living systems on Earth. But what reasons do we have to think that there are further systems that do not belong to the category of "earthbound living system" to which Darwinian evolutionary theory applies too, or to which Darwinian evolutionary models can be applied? Dawkins had a very good reason to assume that *if* extra-terrestrial life were to be found at some point in time, *then* it would probably exhibit Darwinian evolution: the central elements of Darwinian evolution—reproduction, variation in traits between living entities of the same kind, and the need for individual living entities to make a living in a particular environment in which one happens to find oneself (resulting in competition for resources and thus selection)—are such crucial aspects of life that presumably all living systems must exhibit these aspects and thus must also exhibit Darwinian evolution. For Dawkins, then, the scope of Darwinian evolutionary theory was the category of living systems. Dawkins' point was nothing more than that all life exhibits Darwinian evolution—a point that while not a priori true still is highly plausible, but can only be empirically tested when we actually find a sufficient number of instances of extra-terrestrial life. Dawkins basically shifted the question of the applicability of

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[2] As Jagers op Akkerhuis, Spijkerboer, and Koelewijn put it in the present volume, without however endorsing it in this specific form, "evolutionary phenomena in different domains can be viewed as identical in their basic structure if they are analysed at a sufficiently abstract level of analysis" (this volume, Chap. 6). Alternatively, this claim can also be formulated as involving systems rather than processes—Darwinian systems—that are found in a variety of domains and all behave in roughly the same way, making all members of the class susceptible to the same general description with details being filled in differently for different systems.

[3] See, among others, Aldrich et al. (2008) and Hodgson and Knudsen (2006, 2008, 2010).

Darwinian evolutionary theory to the question of the extent of the category of life (or living system). Lacking a univocal or even workable definition of "life" or "living system," however, there does not seem to be a good way to test Dawkins' claim because there seems no way to identify instances of extra-terrestrial life in the first place and to delimit the boundaries of the category of life (or living systems) to which the theory is supposed to apply.

Carol Cleland and coauthors (Cleland and Chyba 2007; Cleland and Zerella 2013) have suggested a way to work around this problem. They have suggested that one aspect of identifying general aspects of all living systems should involve the search for anomalies, i.e., "physical systems resembling familiar Earth life in provocative ways and yet also differing from it in important and unanticipated ways" (Cleland and Zerella 2013: 41). We can work with tentative criteria for what kinds of entities and systems should be considered alive and adapt these criteria on the basis of the anomalous cases we study, where we would have considerable leeway with respect to what we would want to count inside the class of living entities and what as outside. The occurrence of Darwinian evolution could be one of these tentative criteria, and from the study of anomalous cases we can learn exactly how widespread Darwinian evolution is in systems that we are prepared to count within the category of living systems. The problem with this approach, however, is that we do not only lack a sufficient number of suitable anomalous cases, but that we lack potential cases altogether, as so far hardly any candidate cases of extra-terrestrial life have been found and the prospects for finding them do not seem grand.

The problem faced by Universal Darwinism, then, is not that the scope of application of Darwinian evolutionary theory is unclear in any direct way (as the scope of the theory is simply thought to be the category of living systems), but that it is unclear in an indirect way as we have hardly any knowledge about the category of entities to which the theory is thought to apply. So far we only have access to what might or might not turn out to be a small subcategory of the entire category of living systems, namely living systems on Earth. The problem faced by Universal Darwinism thus is ultimately an ontological one: it is the question how the category of living systems is delimited. In the next section, I want to argue that Generalized Darwinism faces a similar problem, but that it occurs as a much stronger version of the problem faced by Universal Darwinism.

7.2 From the Epistemological Problem to Ontological Problems

With the account of Dawkins' Universal Darwinism and Cleland et al.'s view of how the category of life or living systems could usefully be delimited in hand, it is now possible to compare Universal and Generalized Darwinism. Recall that the central question is that of the scope of application of Darwinian evolutionary theory, or at least of models based upon it. The answer provided by Universal Darwinism is that the scope is determined by the category of life, or of living systems, where the open question is how that category is delimited. The suggestion by Cleland and coauthors that we should search for "systems resembling familiar Earth life in provocative ways" (Cleland and Zerella 2013: 41) comes quite close to the claim made by proponents of Generalized Darwinism that there is a particular class of processes or systems that are found in a variety of domains, that differ considerably in the details but that notwithstanding their differences resemble each other sufficiently to allow for a general description to apply to all of them. In both cases, there is an ontological claim regarding the existence of a category of systems (or processes, depending on how one wants to see it) that are the same or resemble each other to a sufficient degree to be describable by means of the same theoretical framework.

The crucial difference between Universal and Generalized Darwinism is that proponents of the former program have a much stronger basis for their ontological claim than proponents of the latter program. Proponents of Universal Darwinism "only" have to solve the problem of delimiting the category of life, or living systems. This is hard enough to do, though. One aspect of the problem, as discussed in the preceding section, is that there is no unequivocal way of determining the category of living beings, that is, a clear set of criteria to distinguish life from nonlife is lacking. Another aspect of the problem is that it is not in fact the category of living beings that we are looking for, as living beings themselves (typically organisms) do not evolve. Rather, it is systems that are composed of such beings (typically populations) that undergo evolution, while organisms reproduce and differentially pass on their traits to the offspring generation. The category of living systems to which Darwinian evolutionary theory can be applied is not identical to the category of living beings, but does depend on it. An additional question thus is how the category of living systems can be delimited once we have established which entities should count as living beings. There thus is a twofold ontological question that needs to be answered by proponents of Universal Darwinism: how is the category of living beings to be delimited and, once that question is satisfactorily resolved, how is the category of living systems that are composed of living beings to be delimited? Current research still is quite a bit removed from having answers to either question.

I want to suggest that what causes Generalized Darwinism to find itself in a worse position that Universal Darwinism is that proponents of Generalized Darwinism have attempted to resolve this problem essentially by fiat—which means, not at all. Proponents of Generalized Darwinism simply claim that there exists a category of Darwinian evolutionary processes or systems that share the same overall structure, no matter on what material basis they are realized and to what extent they might differ in their details. They do not provide support for that claim, however, thus letting it stand as an entirely speculative statement. In one of the core papers of the Generalized Darwinism program, for example, the authors claim that there exist "common abstract features in both the social and the biological world; it is essentially a contention of a degree of ontological communality, at a high level of abstraction and not at the level of detail" (Aldrich et al. 2008: 579). The ontological commonality that the authors refer to at base is the supposed existence of similarities between the structures of the various systems or processes under consideration, such that there is a structurally defined category of processes or systems that can be described by a single, general theoretical framework. In other words, the claim is that in all cases we find the same high-level kinds of things interacting with each other in the same high-level kinds of ways, while at lower (that is, more fine-grained) levels of description large variations in the details exist in how the various processes occur and how the various systems behave. This ontological claim may be correct—if it is, it would support the epistemological claim of Generalized Darwinism that the same general account (a general Darwinian framework, that is) can be used to describe all the processes and systems in the relevant category. The questions that proponents of Generalized Darwinism so far have not answered, however, are (1) what, exactly, the ontological similarities are that the program rests on and whether these are indeed characteristic of Darwinian evolution, and (2) whether these ontological similarities actually exist.[4]

Question (1) is a theoretical question that can be answered by specifying those aspects of Darwinian evolutionary theory that are thought to be the relevant ones. Proponents of Generalized Darwinism have attempted to answer question (1) by pointing to the three core elements of Darwinism, variation, selection, and retention, following Lewontin's well-known triad of phenotypic variation, differential fitness, and heritable fitness (Lewontin 1970).[5] In addition, occasionally the framework of replicators and interactors developed by Richard Dawkins (who spoke of replicators, i.e., typically genes, and vehicles, i.e., typically organisms—see Dawkins 1976, 1982) and David Hull (1980, 1981) is invoked, and it is argued that the basic ontology of replicators and interactors can be found in nonbiological domains as well as in the biological domain (see, for example, Hodgson and Knudsen 2004; Dollimore 2014). The proof of the pudding is in the eating, though, and while this may be an adequate answer to the theoretical question (1) it still remains to be shown convincingly that instances of replicators, interactors, reproduction/retention, and selection *actually exist* in nonbiological domains.[6] That is, while proponents of Generalized Darwinism have potentially identified the kinds of entities and elements that must be present in any case of Darwinian evolution, they have not shown that these entities and elements *actually are present* in nonbiological domains.[7] It is one thing to develop a formal ontology based on replicators, interactors, variation, selection, and

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[4] For a more detailed discussion of aspects of this issue, see Scholz and Reydon (2013) and Reydon and Scholz (2015).

[5] Lacking reproduction in nonbiological systems, reproduction is usually replaced by the retention of traits in the population.

[6] For reasons of space I cannot elaborate this issue in more detail, but see Reydon and Scholz (2014) for some points. Most importantly, proponents of Generalized Darwinism have not yet shown that their candidates for replicators (such as institutional habits), interactors (such as firms and institutions), and reproduction/retention (institutional traits) are indeed sufficiently similar to the parallel aspects of biological evolution such that they would be more than mere superficial analogues between the different domains.

[7] Note my use of the word "potentially." What proponents of Generalized Darwinism have delivered is a potential ontology of Darwinian evolution. But as a potential ontology, it still needs to be shown that it is adequate to the phenomenon that we want to study and understand, i.e., that it is an adequate ontology of Darwinian evolution, irrespective of the additional question in which domains instances of this phenomenon actually are found. In this sense, proponents of Generalized Darwinism have two ontological questions to answer which I highlighted in the main text as (1) and (2). My criticism of Generalized Darwinism is that it does not answer question (2) and only partly answers question (1).

retention, but it is quite another thing to show convincingly that in a particular case (say, the "evolution" of a population of firms) there *actually are* replicators and interactors in any meaningful sense of the terms, and that variation, selection, and retention actually occur in a way that at the very least resembles the ways these occur in biological evolution. Moreover, as a theoretical answer to question (1), the points made by proponents of Generalized Darwinism are quite weak: what proponents of Generalized Darwinism have offered so far is not much more than a rough sketch of what an explanatory evolutionary theory would look like that would cover both biological and nonbiological phenomena, without, however, offering a full-blown theory. And as Levit et al. (2011) have argued, a theoretical framework that only involves the aforementioned bare bones of Darwinian evolutionary theory is insufficiently specific to single out Darwinian processes.

In my view, then, Generalized Darwinism is problematic because it fails to provide adequate answers to its two main ontological questions. This is not to say that such answers could not be provided in the future, it is only to say that at present they are still lacking. The approach suggested by Jagers op Akkerhuis and coauthors, to which I turn next, can be seen as an attempt at answering ontological question (1) by means of a formalized approach. Jagers op Akkerhuis and coauthors do not attempt to answer question (2), that is, they are concerned with setting up a formal structure that specifies the general ontology of all Darwinian evolutionary processes/systems, but they are not concerned with showing that the elements they highlight actually can be found in the various domains in which Darwinian evolution is supposed to occur.

7.3 A Critical Analysis of the Graph-Based Solution

As has been highlighted in the preceding sections, Generalized Darwinism rests on the claim that at some level the various Darwinian evolutionary processes that occur in the natural and the social world are characterized by the same ontology. That is, at some level all instances of Darwinian evolution are supposed to instantiate the same overarching structure in which the same high-level kinds of material entities interact with each other in the same ways. Jagers op Akkerhuis and coauthors now claim that this general structure of Darwinian evolutionary processes can be represented by means of graph diagrams (Chaps. 4 and 6 in the present volume). Their approach thus is in the same spirit as the approach of the main proponents of Generalized Darwinism, in that all try to specify elements of the general structure of Darwinian processes/systems. The difference is that while proponents of Generalized Darwinism take recourse to theoretical concepts developed in biology and in the philosophy of biology, Jagers op Akkerhuis and coauthors take recourse to a widely used modeling tool.

The main claims made by Jagers op Akkerhuis and coauthors are that the basic structure of Darwinian evolution can be represented by means of structured graphs, that two basic kinds of such graphs can be used (object-based and kind-based graphs), and that the representation of evolution by means of graphs is sufficiently abstract to constitute a general representation of evolution that can be applied to all instances of evolution, both within and outside the biological domain. Jagers op Akkerhuis and coauthors thus do not focus primarily on the process aspects of Darwinian evolution, but rather focus on the entities that play a role in evolutionary processes (or that undergo evolution) and the various relations that exist between them, using graphs to represent these entities (as the nodes of graphs) and relations (as the connecting lines between the nodes) in the context of the overarching structure of an evolving system. While this clearly is a possible way to represent evolution—be it evolutionary processes, evolving systems, or perhaps only some elements of evolution such as natural selection—it remains to be seen whether it can serve as a sufficient foundation for Generalized Darwinism. I want to suggest that it cannot.

It should be noted that Jagers op Akkerhuis and coauthors do not only aim at laying a foundation for Generalized Darwinism, but also aim to lay a foundation for *defining* Darwinian evolution as such. As they put it in Sect. 4.2 of the present volume, "we suggest that an object-based graph approach also has a role to play [...] as a theoretical foundation for defining the concept of Darwinian evolution". This goal of their work is part of their approach to generalizing Darwinism, namely to create formal definitions of all the relevant elements of Darwinian evolution and on the basis of these general definitions to construct a general formal structure. As Jagers op Akkerhuis and coauthors say in Sect. 4.3.5 of this book, "The goal of this book is to create definitions that are general" and to be sure, the creation of general definitions is a crucial step on the way to constructing a workable Generalized Darwinism. In that respect perhaps the aims of defining Darwinian evolution and of generalizing Darwinism coincide: once one has obtained a definition of Darwinian evolution one has delimited the class of phenomena (or systems, or entities, or processes, depending on the definition) that one is interested in in such a way that class membership is fixed and the scope of the general formalism is also fixed. That is, one has defined what Darwinian evolution is (and what it is not) such that one can identify instances of Darwinian evolution in any domain by simply measuring a candidate instance against the definition. Darwinism then is generalized to precisely the extension of the class of phenomena. Jagers op Akkerhuis and coauthors in this way provide an answer to the ontological question (1) that was explicated above, but their answer in my view faces the same problems as that of other proponents of Generalized Darwinism.

Recall from Sect. 7.2 that the principal problem faced by proponents of Generalized Darwinism is that although they have potentially identified the kinds of entities and elements that must be present in any case of Darwinian evolution, they have not shown that these entities and elements actually are present in nonbiological domains. But, as was pointed out in Sect. 7.2, a different problem has to be addressed first. The first question to be addressed is whether the ontology that is developed (be it the ontology of replicators, interactors, etc. in Generalized Darwinism, or the graph-based ontology of Jagers op Akkerhuis and coauthors) is adequate to what we already mean by Darwinian evolution. This is a question of *theoretical adequacy* of the ontology that is developed to the scientific theory that describes Darwinian evolution, i.e., well-established biological evolutionary theory. The second question then is whether the elements of the developed ontology actually exist in the nonbiological domains under consideration and whether these actually interact with each other in such ways that instances of Darwinian evolution can be found in different domains. This is a question of *empirical adequacy* in the nonbiological domain under study of both the developed ontology and the scientific theory for which it was developed. Both questions are ontological but have to be answered in different ways.

In what follows I want to focus on the first question. The second question arises once the formalism has been developed adequately for biological cases and then is to be addressed on a case-by-case basis. That is, for every new attempt at applying Darwinian evolutionary theory to a particular phenomenon the second ontological question poses itself anew and has to be answered independently of how it was answered in other cases. It should be noted, though, that I am not suggesting that one can simply take each and every possible case of biological evolution as an unquestioned member of the class and examine the appropriateness of adding members only for nonbiological cases. For potential cases of Darwinian evolution from the biological realm, too, the second question has to be addressed. However, one has to start somewhere and in this particular case the best place to start is those uncontested cases in biology for which Darwin developed his theory, and later biologists continue to use it. The general idea, then, is, to take Darwinian evolutionary theory (in its currently most widely used form) and the paradigmatic cases of Darwinian evolution that are accounted for by this theory, and extend and revise the class by adding as well as occasionally removing cases.[8] The theoretical adequacy mentioned above is the requirement that any putative case of Darwinian evolution must be susceptible to being accounted for by currently accepted evolutionary theory.[9]

The first question seems more pressing, because what is at stake here is the theoretical adequacy of the developed ontology independently of its application to biological and nonbiological cases. As Jagers op Akkerhuis and coauthors aim to define all elements of Darwinian evolution and by doing so also to define Darwinian evolution itself, their first aim should be to highlight what all the different instances of biological evolution have in common in order to achieve a solid basis for their definition that does not fail to cover any instances of Darwinian evolution that occur in the biological domain. From there onward the definition can be extended to cover putative cases of Darwinian evolution outside the biological domain. But in this respect the approach presented by Jagers op Akkerhuis and coauthors runs the risk of being overly a priori and insufficiently naturalistic. While for modeling purposes unequivocal and strict definitions are required as the basis for the model that is to be developed

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[8] Jagers op Akkerhuis (personal communication) also advocates this approach.

[9] Evolutionary theory is not as such stable through time, but rather is susceptible to considerable change and quite a number of competing versions of evolutionary theory have been advanced in the history of biology. While currently the Modern Synthesis version of the mid-twentieth century still is the most widely used version by biologists, numerous attempts are being made to change, revise, and/or extend Darwinian evolutionary theory (see, e.g., Jablonka and Lamb 2005; Pigliucci and Müller 2010). While theoretical adequacy thus is a requirement on the ontology, this requirement itself is to some extent fluid in time as the theoretical basis changes under the influence of new developments in biology.

to study a particular phenomenon, it seems to me that such definitions are not suited to serve as the basis for an overarching model that would cover the entire category of Darwinian evolutionary phenomena, as this is an empirically delimited category of phenomena. The category of Darwinian evolutionary phenomena in the biological domain is quite heterogeneous: evolution in mammals proceeds differently from evolution in social insects, for example, and evolution in microbial populations is quite different from evolution in animals, which differs considerably from evolution in plants. This means that any project of developing a definition of Darwinian evolution should start by examining the diverse spectrum of cases that we usually count as instances of Darwinian evolution, identify relevant theoretical similarities between those cases, and build a definition on the basis of these similarities.

Jagers op Akkerhuis and coauthors use graphs to represent patterns of evolution and as such their project is to highlight a set of patterns that is found in all and only instances of Darwinian evolution. The question that poses itself for their approach thus is whether the sought-after definition of Darwinian evolution can be developed by examining patterns of the sort that Jagers op Akkerhuis and coauthors focus on, that is, whether these patterns can adequately highlight the relevant similarities between the various instances of Darwinian evolution in the living world. Jagers op Akkerhuis and coauthors examine two overarching kinds of graphs, object-based graphs in which the nodes are entities and kind-based graphs in which the nodes are kinds. Kind-based graphs are more general than object-based graphs (Sect. 6.2.5), such that one might proceed stepwise by constructing object-based graphs of concrete instances of biological evolution, kind-based graphs that collect sufficiently similar object-based graphs, and so on until the most general level of Darwinian evolution is reached.

There are, however, important differences between the ontologies associated with the two cases and it is not clear whether the step from object-based graphs to kind-based graphs can be taken easily. In the case of object-based graphs in which the nodes represent the organisms in a population, for example, the graphs can be interpreted as simple genealogical trees showing ancestor-descendant relationships between organisms while the graph represents the genealogical history of the population. The same holds for other biological entities such as the cells of a developing organism: an object-based graph of the cells of an organism would represent the genealogical history of the organism's cells. As such, object-based graphs ontologically represent the *historical products* of the evolutionary process, namely lineages of concrete genes, cells, organisms, etc. As such, object-based graphs can be combined into more detailed mixed graphs. The nodes of an organism-level graph can, for instance, be replaced by sets of developmental rules to yield more fine-grained graphs in which organisms are not treated as black boxes but some details of their internal developmental process are being represented too. So far, so good.

In the case of kind-based graphs in which the nodes represent kinds of biological objects, however, the ontology is much less straightforward. When nodes are taken to represent kinds of biological entities, for example when the nodes are taken to represent species of organisms, the question arises whether biological kinds are ontologically suited to function as nodes in evolutionary graphs. In commonly used causal graphs, for example, nodes represent variables (parameters) that causally affect each other. In object-based graphs such as described by Jagers op Akkerhuis and coauthors nodes represent entities that interact with each other. But in kind-based graphs it is not a priori clear that the kinds or groups of entities that are represented by a graph's nodes are of the sort that can interact with each other. For the case of species, for example, it remains an unresolved issue whether species can be conceived of as entities in selection processes, that is, as interactors or replicators (for arguments in favor, see for example Lloyd and Gould 1993; Gould 1998; Gould 2002: Chap. 8). Jagers op Akkerhuis and coauthors impose the requirement that for a kind to be able to function as a node in a kind-based graph it must be a strictly determined kind without any indeterminacy with respect to the kind membership of individual entities. As they put it: "If one uses kinds as nodes, one has to be cautious that all the objects represented by the kind comply without exception with the criteria for the kind." (Sect. 6.2.5). On the basis of this restriction Jagers op Akkerhuis and coauthors exclude species as suitable kinds to appear in kind-based graphs. But I would want to suggest that the actual reason to exclude species and possibly most other kinds of biological entities from appearing as nodes in graphs is a different one. It is questionable whether the restriction imposed by Jagers op Akkerhuis and coauthors itself is able to guarantee that a kind will be able to occupy the position of a node in a kind-based graph. After all, the issue is ontological—the issue is whether species can be conceived of as individuals of the sort that can interact with each other in any meaningful sense of the term. Kinds cannot interact with other kinds, only their members (as concrete individuals) can interact with one another. Thus, any kind-based graph in which species occur as the nodes would actually represent interactions between individual member entities of the species involved, rather than between the species themselves, except in the case in which species themselves are conceived of as concrete individuals. As it stands, this remains an unresolved issue in the philosophy of biology as well as in theoretical biology itself. Thus, there seems to be an ontological gap between those levels of the biological hierarchy that can be described by means of object-based graphs and those levels that are best described by kind-based graphs, and it is not clear whether the Darwinian processes that object-based graphs are supposed to represent also occur on the levels described by kind-based graphs. This implies that the step from object-based graphs to kind-based graphs and the generalization of Darwinism that seems to hinge on the construction of high-level kind-based graphs cannot be made as long as the ontological questions regarding the nature of the kinds and groups involved remain unresolved.

7.4 Conclusion

While in the present paper I have only been able to examine one aspect of the proposal by Jagers op Akkerhuis and coauthors, I have discussed two ontological questions that I believe are central in any attempt to develop a Generalized Darwinism. I have discussed these questions about the version of Generalized Darwinism that is found in the literature and have suggested that the version developed by Jagers op Akkerhuis and coauthors suffers from the same problems. This is not to say that the ontological questions cannot be answered. But it is to say that any version of Generalized Darwinism needs to answer them first, and that as long as answers are lacking or only given in a speculative manner the approach in question will not get off the ground. And so far, unfortunately, proponents of Generalized Darwinism have failed to provide satisfactory answers.

References

Aldrich HE, Hodgson GM, Hull DL, Knudsen T, Mokyr J, Vanberg VJ (2008) In defence of generalized Darwinism. J Evol Econ 18:577–596

Cleland CE, Chyba CF (2007) Does ‘life’ have a definition? In: Sullivan WT, Baross JA (eds) Planets and life: the emerging science of astrobiology. Cambridge University Press, Cambridge, pp 119–131

Cleland CE, Zerella M (2013) What is life? In: Kampourakis K (ed) The philosophy of biology: a companion for educators. Springer, Dordrecht, pp 31–48

Dawkins R (1976) The selfish gene. Oxford University Press, Oxford

Dawkins R (1982) Replicators and vehicles. In: King’s College Sociobiology Group (ed) Current problems in sociobiology. Cambridge University Press, Cambridge, pp 45–64

Dawkins R (1983) Universal Darwinism. In: Bendall DS (ed) Evolution from molecules to men. Cambridge University Press, Cambridge, pp 403–425

Dawkins R (2008) Why Darwin matters. The Guardian, Saturday 9 February 2008

Dollimore DE (2014) Untangling the conceptual issues raised in Reydon and Scholz’s critique of Organizational Ecology and Darwinian populations. Philos Soc Sci 44:282–315

Gould SJ (1998) Gulliver’s further travels: the necessity and difficulty of a hierarchical theory of selection. Philos Trans R Soc Lond B Biol Sci 353:307–314

Gould SJ (2002) The structure of evolutionary theory. Harvard University Press, Cambridge, MA

Hodgson GM, Knudsen T (2004) The firm as an interactor: firms as vehicles for habits and routines. J Evol Econ 14:281–307

Hodgson GM, Knudsen T (2006) Why we need a Generalized Darwinism and why a Generalized Darwinism is not enough. J Econ Behav Organ 61:1–19

Hodgson GM, Knudsen T (2008) In search of general evolutionary principles: why Darwinism is too important to be left to the biologists. J Bioecon 10:51–69

Hodgson GM, Knudsen T (2010) Darwin’s conjecture: the search for general principles of social and economic evolution. University of Chicago Press, Chicago

Hull DL (1980) Individuality and selection. Annu Rev Ecol Syst 11:311–332

Hull DL (1981) Units of evolution: a metaphysical essay. In: Jensen UJ, Harré R (eds) The philosophy of evolution. The Harvester Press, Brighton, pp 23–44

Jablonka E, Lamb MJ (2005) Evolution in four dimensions. Genetic, epigenetic, behavorial and symbolic variation in the history of life. MIT Press, Cambridge, MA

Levit GS, Hossfeld U, Witt U (2011) Can Darwinism be “generalized” and of what use would this be? J Evol Econ 21:545–562

Lewontin RC (1970) The units of selection. Annu Rev Ecol Syst 1:1–18

Lloyd EA, Gould SJ (1993) Species selection on variability. Proc Natl Acad Sci U S A 90:595–599

Pigliucci M, Müller GB (eds) (2010) Evolution—the extended synthesis. MIT Press, Cambridge, MA

Reydon TAC, Scholz M (2014) Darwinism and organizational ecology: a case of incompleteness or incompatibility? Philos Soc Sci 44:364–373

Reydon TAC, Scholz M (2015) Searching for Darwinism in generalized Darwinism. Br J Philos Sci 66:561–589

Scholz M, Reydon TAC (2013) On the explanatory power of Generalized Darwinism: missing items on the research agenda. Organ Stud 34:993–999

Chapter 8
The Role of Structural Criteria in Transitions Theory: A Focus on Organisms

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> *'In attempting to distinguish organisms from parts and from groups, authors often list qualities that typify organisms, but usually also recognize the many exceptions to these general patterns. Many such qualities fail as definitional criteria on the grounds that they are necessary for recognizing an organism, but not sufficient because they also are met by many non-organisms'*
>
> (Pepper and Herron 2008).

Abstract The Major Evolutionary Transitions theory of Szathmáry and Maynard Smith is famous for its contribution to the understanding of complex wholes in biology. Typical for Major Evolutionary Transitions theory is the select use of functional criteria, notably, cooperation, competition reduction and reproduction as part of a larger unit. When using such functional criteria, any group of attached cells can be viewed as multicellular, such as a plant or the slug-shaped aggregation of cells of a slime mould. In addition, one could also have used structural criteria to arrive at the conclusion that the cells in the slug of a slime mould are attached without plasma strands, while the cells of a plant are attached and connected through plasma strands. A theory which in addition to functional criteria also uses structural criteria for the identification of major transitions is the Operator Theory. Using the Operator Theory one can, for example, conclude that the slug of a slime mould represents a pluricellular organisation because its cells are not connected through plasma strands, while the cells of a plant are connected through plasma strands and for this reason represent a multicellular organism. In this chapter, the relationships between the Major Evolutionary Transitions theory and the Operator Theory are studied with a focus on transitions that lead to organisms.

8.1 Introduction

The search for explanations for individuality and wholes in nature has a long history. Early authors in this field are Stebbins (1969) and Bonner (1974), while Buss (1987, p 171) suggested 'a history of transitions between different units of selection'

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_8

including the 'association of autonomously-replicating molecules to self-replicating complexes, the incorporation of such complexes into cells, the establishment of a multi-genomic cell via incorporation of autonomously replicating organelles and, with the evolution of sexuality, the origin of species.' Later, Maynard Smith (1988) discussed levels of selection and evolution, after which Maynard Smith and Szathmáry (1995) published 'The major transitions in evolution'. Szathmáry (2015) has published a version 2.0 of the approach, with recent updates. The Major Evolutionary Transitions theory has provided a basis for thoughts about transitions, about levels of complexity and about the emergence of complex units that have inspired many scientific publications (e.g., Calcott and Sterelny 2011; Bourke 2011; Bouchard and Huneman 2013; West et al. 2015).

The Major Evolutionary Transitions theory has also provoked criticism which may well deserve some attention. For example, McShea has suggested that the major transitions are inconsistently defined and that it can be questioned whether the criteria it uses offer a sufficient basis for defining individuality (McShea and Simpson 2011). Which are the criteria the Major Evolutionary Transitions theory uses for the identification of a major transition? Basically, every major transition is said to comply with three criteria: cooperation, competition reduction and replication as parts of a larger unit after the transition (Maynard Smith and Szathmáry 1995). Each of these three criteria refers to a process and can be viewed as a functional criterion for this reason. The kind of the larger unit is not specified. Through the select application of functional criteria, and by leaving undefined the kind of larger unit, the Major Evolutionary Transitions theory realises a very general applicability. However, the generality of the criteria of Major Evolutionary Transitions theory also leads to ontological ambiguity. This ambiguity can be illustrated by the following example. If one focuses on cooperation, competition reduction and reproduction as part of a larger unit, such criteria fit equally well to the transition from cells to a multicellular organism, as to the transition from bees to a bee colony. A multicellular organism and a colony are not the same, however, because a bee represents a physically integrated unity that has a single body, whilst the colony is a result of behavioural interactions between many bees, each having a proper body. As Major Evolutionary Transitions theory is selectively based on functional criteria, it is insensitive to structural differences, such as that exist between a bee and a colony of bees.

As an exploration of the effects of adding structural criteria, the relationships between the Major Evolutionary Transitions theory (Maynard Smith and Szathmáry 1995) and the Operator Theory (Jagers op Akkerhuis and van Straalen 1999) can serve as a test case. When relating these two approaches the Operator Theory can be viewed as offering an interesting reference, because it is based on criteria that have been defined independently of the Major Evolutionary Transitions theory. The criteria of the Operator Theory are not based on cooperation, competition reduction and reproduction as part of a larger unit, but on special functional and special structural criteria that are combined in the concept of dual closure (see Chap. 2). The idea of this chapter is that by relating the two approaches, thoughts about individuality, transitions and hierarchy can be advanced. In the current chapter, the focus is on objects, such as organisms, while the next chapter will focus on groups of interacting organisms.

8.1.1 *Outline of This Chapter*

First, it is summarised how the Major Evolutionary Transition theory and the Operator Theory deal with the concept of individuality. These insights form a basis for the classification of transitions inside objects, and transitions between kinds of objects, and for a discussion of the relationships between the two theories.

8.2 Major Evolutionary Transitions that Relate to Organisms

As the driving force behind major evolutionary transitions, it is suggested that a new unit must have advantages, for example because it is more efficient because of the division of labour and/or the combination of functions. After the subtraction of costs of interactions, the unit rewards its members through a net fitness increase, which forms the basis for the synergism hypothesis (Corning 1983; Corning and Szathmáry 2015). At the same time, there is the risk that the synergy of the group will be abused by parasitic elements, called free riders. To prevent free riders, mechanism must evolve which reduce internal competition, in a process of de-Darwinisation (Godfrey-Smith 2009). After having been de-Darwinised the elements of the group may reproduce as part of the larger unit. At that moment, the criteria/features of cooperation, competition reduction and reproduction as part of a larger unit are all met. With respect to the question of whether or not all these criteria must be met, Szathmáry (2015) indicates that: ‘It has never been claimed that all transitions would possess all common features or that the possessed features would have uniform weights across all of the transitions’. In our view, such reservations imply that, in principle, many processes can comply with one or more of the criteria, and that the concept of a major evolutionary transition is not very specific, for this reason.

In this chapter, the focus will be on major evolutionary transitions which lead to organisms (Table 8.1). To illustrate the historical development of insights, the first column of Table 8.1 summarises the original major transitions of Maynard Smith and Szathmáry (1995), while the second column summarises the major transitions in the improved 2.0 version (Szathmáry 2015).

8.3 Transitions in the Operator Theory That Are Relevant for the Identification of Organisms

This book uses the Operator Theory (Jagers op Akkerhuis and van Straalen 1999) as an external reference for how the Major Evolutionary Transitions theory defines transitions, individuality and organismality. As has been explained in Chap. 2 the Operator Theory offers a generic methodology for the creation of a hierarchy of a special kind of material objects called operators. Since Jagers op Akkerhuis and van Straalen (1999) a range of studies has been published which discuss aspects of the Operator Theory (e.g., Jagers op Akkerhuis 2008, 2010a, b, 2012a, b, 2014).

Table 8.1 Transitions that relate to organisms Relationships between the major evolutionary transitions as proposed by (Maynard Smith and Szathmáry (1995) and Szathmáry (2015) and the Operator Theory as proposed by Jagers op Akkerhuis and van Straalen (1999)

Major transitions (original version) (1995)	Major transitions (version 2.0) (2015)	Operator hierarchy (1999–2016) Kind of operator involved in the transition	Operator theory (2008–2016) Object of study is: – An operator – A compound obj. – A group	Operator theory (2008–2016) Dimensions: – Upward dimension – Inward dimension – Outward dimension
Replicating molecules to populations of molecules in compartments	Proto-cell	From molecules to the construction of the cell	Operator (cell)	Upward dimension: Integration to the next level operator
Unlinked replicators to chromosomes	Genetic code and translation: prokaryotic cells	Change inside the cell, involving molecular operators	Operator (cell)	Inward dimension: Transition takes place inside a cell
RNA as gene and enzyme to DNA and protein	Genetic code and translation: prokaryotic cells	Change inside the cell, involving molecular operators	Operator (cell)	Inward dimension: Transition takes place inside a cell
Prokaryotes to eukaryotes	Eukaryotic cells (cells with mitochondria)	Construction of cell with endosymbiont (the operator kind is called the endosymbiont cell)	Operator (endosymbiont cell)	Upward dimension: Integration to the next level operator
	Plastids	Entering of additional endosymbiont (the operator is still an endosymbiont cell)	Operator (endosymbiont cell)	Upward dimension: Integration to the next level operator
		Multicellular (based on bacterial cells, e.g. Bluegreen algae)	Operator (multicellular)	Upward dimension: Integration to the next level operator
Protists to animals, plants and fungi	Multicellularity	Construction of the endosymbiont multicellular (fungi, algae, plants)	Operator (endosymbiont multicellular)	Upward dimension: Integration to the next level operator
		Construction of Neural network organism (multicellular animal or, in terms of the Operator Theory, a memon)	Operator (memon)	Upward dimension (while occurring inside a multicellular): Groups of neurons realise second order recurrent interactions with interface of sensors and create the next level operator

Grey and white boxes in the rightmost column indicate the upward (grey) or inward dimensions of the Operator Theory (as explained in Chap. 2). A complete Table for operators and interaction systems can be found in Appendix

The Operator Theory and its consequences for hierarchy theory were discussed in Chap. 2. Because the Operator Theory forms the basis for the current process of relating the Major Evolutionary Transitions theory and the Operator Theory, the following lines offer a short summary of the innovations of the Operator Theory.

Every step up the Operator Hierarchy is defined by means of the combination of a specific circular process referred to as functional closure, and a specific circular structure referred to as structural closure (as explained in Jagers op Akkerhuis 2010a). The combination of structural and functional closure defines the conceptual limitation of an operator as a unity, and is referred to as *dual closure*. Past publications about the Operator Theory have also referred to dual closure in terms of closure, or first possible next closure. The concept of dual closure adds a novel principle to the classical thinking about individuality and hierarchy (e.g., Von Bertalanffy 1950; Simon 1962; Turchin 1977; Koestler 1978; Miller 1978; Salthe 1985; Heylighen 1990; Alvarez de Lorenzana 1993).

The Operator Theory uses three dimensions for analysing increases in complexity: (1) Levels of complexity and transitions inside an organism (or inside any other operator, e.g., organ formation) are viewed as taking place along the so called inward dimension. (2) Levels of complexity and transitions from one organism kind to the next, e.g., from cell to multicellular, are ranked along the so called upward dimension. (3) Transitions from organisms to interaction systems, e.g., from plant to ecosystem, are viewed as taking place along the so called outward dimension, and involve different kinds of processes that lead to groups.

The Operator Hierarchy has helped in solving the long-standing challenge of defining the organism concept. For this purpose, all the operators from the level of the cell and up are viewed as organisms, as has been explained in Chap. 2 (see also Jagers op Akkerhuis 2010b, 2012a, b).

Finally, the Operator Theory offers a fundamental and nested ontology of system kinds (Fig. 8.1) which includes the following top level classes: the operators and the interaction systems (Jagers op Akkerhuis 2008). The set of interaction systems has many subsets, for example compound objects, the behavioural compound object (groups of attached organisms) and behavioural groups.

8.4 Classifying Different Combinations of Cells

The ontology of the Operator Theory can be used to analyse in detail the transitions from cells to endosymbiont cells and to multicellular organisms (Fig. 8.2). Starting with the cell, different kinds of endosymbiont cells may form. In order to comply with dual closure, the symbiotic relationship must be obligatory for all parties involved. One can speak of a parallel endosymbiont when two different kinds of cells inhabit the same host, of which the mitochondria and chloroplasts in plants are an example. One can speak of a higher order endosymbiont when a cell hosts a cell, which itself also hosts a cell. As reviews by, e.g., Bardele (1997), Chan and Bhattacharya (2010), Keeling (2010), and Gagat et al. (2014) indicate, nature has experimented with many different endosymbiont constructions.

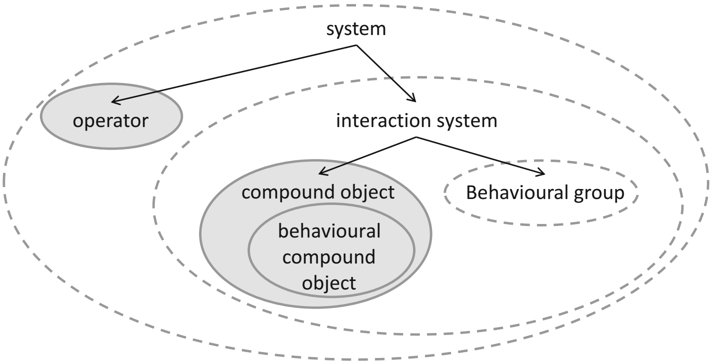

Fig. 8.1 A hierarchy of kinds of systems based on the ontology of the Operator Theory. Subsets with *broken lines* represent conceptual entities. Subsets with *grey shading* and *solid lines* indicate classes of which every example represents a single physical object

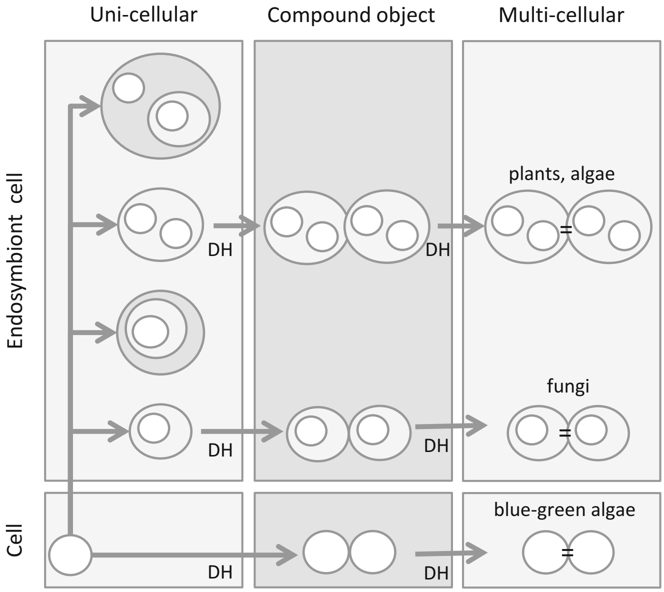

Fig. 8.2 Explanation of the transitions in the Operator Hierarchy that lead to the formation of different kinds of organisms. *Vertical arrow*: from cell to endosymbiont cells of the first or higher order (classically named eukaryote cell). *Horizontal arrows*: from unicellular organisation to multicellular organisation. *Arrows* that are part of a developmental history are marked DH. Plasma connections are indicated by the = symbol. *Square boxes with light shading*: organisms. *Square boxes with darker shading*: compound objects

In addition to the formation of endosymbiont organisms, a route can be distinguished towards multicellular organisms (Fig. 8.2). This route is driven by advantages of the grouping of cells (size, physiology, etc.). In the Operator Theory, the presence of plasma strands between the cells is viewed as the decisive criterion for multicellularity. When the cells are not connected through plasma strands, the

Operator Theory considers the ensemble as a compound object, and refers to it as a pluricellular structure, instead of as a multicellular structure. Plasma strands may have evolved in a scaffolded process, as part of a developmental history starting with clonal offspring, which are full kin and share a common interest in reproduction. Once that plasma strands have formed between the clonal cells this allows tightening of cooperation and an increase in competition reduction.

Several organisations are not included in Fig. 8.2. For example, the pluricellular slug of a slime mould is not included, because its cells lack plasma strands. Figure 8.2 neither includes animals with neural networks, because, according to the logic of the Operator Theory, the neural network and the sensors that surround it represent a higher order of dual closure than that of multicellularity.

8.5 Discussion

This chapter will focus on the relevancy for transition theory of structural criteria. To examine the role of structural criteria, the differences in viewpoints will be examined of the schools of Major Evolutionary Transitions theory and the Operator Theory. Firstly, attention will be paid to transitions that result in the formation of organisms and that are not shared between Major Evolutionary Transitions theory and the Operator Theory. Secondly, it will be discussed how Major Evolutionary Transitions theory and the Operator Theory suggest that the organism concept can be defined. Thirdly, the difference between pluricellularity and multicellularity will be discussed in detail. And finally, it will be examined which of the two theories is least prone to arbitrary changes in its structure.

8.5.1 Relating the Major Evolutionary Transitions Theory and the Operator Theory While Focusing on Organisms

Table 8.1 offers a summary of the relationships between the Major Evolutionary Transitions theory (Szathmáry and Maynard Smith 1995; Szathmáry 2015) and the Operator Theory (Jagers op Akkerhuis and van Straalen 1999) while focusing on organisms. Some classes can be found in both approaches, e.g., the bacteria/prokaryote cells, the eukaryote cells and—with a difference in the interpretation—the multicellulars. On other points the two classifications differ.

One aspect in which the approaches differ is that some major transitions in Table 8.1 lack a counterpart in the operator hierarchy; for example, the proto-cell, indicating a cell without chromosomes. From the viewpoint of the Operator Theory, the emergence of chromosomes may occur inside an already existing cell, and is recognised therefore as an internal differentiation. According to the logic of the Operator Theory, the combination of 'proto' and 'cell' would imply incomplete dual closure, such as an autocatalytic set in a droplet without a membrane, or a membrane surrounding a volume of which the chemistry is not autocatalytic.

A system with incomplete dual closure would not meet the criterion of dual closure, and could not be viewed as an organism for this reason. The Major Evolutionary Transitions theory additionally views the shift from cells based on RNA to cells based on DNA as a major transition, while the Operator Theory again classifies this transition as an internal differentiation.

An inverse analysis indicates that some classes in the Operator Theory have no corresponding major transition. Examples are the prokaryotic multicellular and the neural network organism. As the Operator Theory is based on dual closures, and closure dimensions, the existence of a cell implies the potential existence of a multicellular form. This logic suggests that two kinds of multicellular organisms can be imagined: one consisting of cells, and another consisting of endosymbiont cells. If one now compares the Major Evolutionary Transitions theory and the Operator Theory, the transition to endosymbiont multicellularity can be found in both approaches. Meanwhile, the multi-cellular based on (prokaryotic) cells, such as some filamentous cyanobacteria (blue-green algae), seems to be absent from the major evolutionary transitions scheme. The reason why the Operator Theory views such cyanobacteria as multicellulars is that dual closure is realised the moment that normal cells and nitrogen fixing cells, called heterocysts, are connected through plasma strands, which, e.g., Giddings and Staehelin (1978) refer to as micro-plasmodesmata.

Another class which is exclusively present in the ranking of the Operator Theory is that of the multicellular with a nervous system, which the Operator Theory refers to as the memon (e.g., Jagers op Akkerhuis 2008). Memons emerge when—in the multicellular environment—neurons form groups of distantly interconnected cells which in turn interact with other such groups, and in this way allow for a second-order recurrent (hypercyclic) interactive process. The structural limit to the neural network organism is formed by sense organs (for more details see Jagers op Akkerhuis 2010a). The Operator Theory rejects the formation of a memon through the cooperation of multicellular organisms (e.g., plants). The reason is that such cooperation would not represent the next dual closure, because cooperation between organisms, e.g. plants, that consist of linked cells, would result in a larger organism consisting of linked cells, not in a new kind of organization. Dual closure thus offers a different perspective on transitions than that of cooperation, competition reduction and reproduction. While in the Operator Theory the neural network organism represents a separate kind of organism, Szathmáry (2015) discusses the nervous system as a limited transition, more specifically a filial transition, allowing for a new Darwinian system, just as the immune system. Meanwhile, the Operator Theory views the immune system as an internal differentiation with evolutionary capacity.

8.5.2 The Organism, the Fundamental Object in Biology

The concept of the major transition applies both to the emergence of the first cell, the emergence of endosymbiont cells and the emergence of plants, which are all organisms. Some schools observe that some major evolutionary transitions lead to organisms, and generalise this observation by suggesting that major transitions offer suitable criteria for the formation of an organism. For example, Queller and

Strassmann (2009) use cooperation and competition reduction for suggesting that some social insect colonies, some microbial groups and some mutualistic associations classify as organisms. The use of the word ‘some’ already indicates that the relationship cannot be used in a general way. Meanwhile, the Operator Theory uses different criteria for identifying which systems are organisms, and suggests that only the operators that are at least as complex as the cell are to be viewed as an organism. According to this viewpoint, it is not valid to suggest that some colonies or some mutualistic associations may qualify as organisms, because the systems involved fail to classify as an operator.

Another challenge if one uses functional criteria for defining the organism concept is that one has to deal with varying degrees of cooperation, competition reduction and reproduction as part of a larger unit. As a solution, a school in recent literature advocates that organismality can be realised to varying degrees. In relation to this viewpoint, Santelices (1999) discusses multidimensional spaces for introducing variability into parameters of individuality. And Pepper and Herron (2008) reviewed criteria used for recognising organisms and concluded that the reviewed criteria ‘are not categorical but rather continuously variable’ and they described combinations of frequently co-occurring traits as an organism syndrome. A related reasoning is followed by Godfrey-Smith (2009) suggesting that it would be better to talk about a ‘degree of organismality’ than about whether something is or is not an organism. In line with this, Godfrey-Smith (2009, 2013) ranks what he calls collective reproducers, such as volvox, humans, slime moulds, sponges and buffalo herds, according to a higher or lower score on the following parameters: (1) a reproductive bottleneck, (2) reproductive specialisation (soma/germline) and (3) overall integration.

The viewpoint of the gradualist school is not free of criticism. Specific objections are offered by Booth (2014), indicating that the utility of applying gradualism to a eukaryotic organism and its associated microbes, which together are also indicated as a holobiont, can be questioned because it offers no precise information about what kinds of causal interactions bind parts into interactors. Moreover, the conceptual payoff of discussing interactors, units of selection, or Darwinian individuals would not be clear if co-evolutionary approaches may already explain the origin of holobionts. In the light of such debate, the Operator Theory offers an innovative solution, by relating the organism concept strictly and only to any operator of the level of the cell and higher in the Operator Hierarchy (e.g., Jagers op Akkerhuis 2010b, 2012a, b). This simple definition indicates a precise range of kinds of operators which classify as organisms. Moreover, from an ontological perspective, the operator-based definition solves ambiguity because it allows a clear distinction between organisms, and systems of interacting organisms.

8.5.3 Multicellularity Versus Pluricellularity

Szathmáry (2015) cites Cartwright (2013) stating that ‘Ultimately, what allows organism formation from lower level units is a high level of cooperation and a low level of realized conflicts’. This citation strongly suggests that cooperation and competition reduction are viewed as criteria for organismality. However, and as was already indicated several times in this chapter, the select use of such criteria would imply that both slime moulds, plants and Lichens classify as organisms, or would be on their way to becoming organisms, because the cells show cooperation and competition reduction. The viewpoints of the Operator Theory on this matter are different, because it uses plasma connections as the criterion for multicellularity. For example, a plant consists of cells which are connected through plasma connections, for which reason a plant classifies as an operator/organism. Meanwhile, the literature does not seem to offer any information confirming that the cells of the slug of the slime mould are connected through plasma connections. Therefore, the Operator Theory does not classify the slug of a slime mould as a multicellular organism. Instead, the slug represents a pluricellular organisation, and is viewed as a compound object. Finally, the example of Lichen refers to a system which consists of interwoven hyphae of a multicellular fungus, which grow around individual cells of an alga. There are no plasma connections between the algal cells and the fungal cells. Accordingly, the algal cells and the fungal cells classify as separate operators/organisms, which have co-evolved into a structurally integrated compound object.

8.5.4 How Arbitrary Is a Listing of Transitions?

In his recent update of the Major Evolutionary Transitions theory, Szathmáry (2015) discusses the use of listings of major evolutionary transitions, stating that: ‘A list by itself can be defined in any arbitrary way; the crucial question is how the listed items belong together’. In major transitions theory all transitions comply with the functional criteria of cooperation, competition reduction and reproduction as part of a larger unit. Such a focus on functional criteria does not take structural aspects into account. The exclusion of structural criteria leads to ambiguity about which systems can be viewed as being the result from a major transition. Meanwhile, the definition of every kind of operator is based on a specific level-dependent dual closure, such that all transitions form a stringent sequence. The structure of the Operator Hierarchy is furthermore supported by the observation that all transitions of the Operator Theory are not only explained by dual closure, but also seem to have a place in a meta-pattern of recurring closure dimensions, as was explained in Chap. 2.

The difference in the criteria that are used by either method also seems to result in differences in the number of updates. Table 8.1 demonstrates that compared to the publication of Maynard Smith and Szathmáry (1995) both the number of classes and the definitions of several of the classes in Szathmáry (2015) have changed. Meanwhile, the structure of the operator hierarchy has undergone very little change since 1999 (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2012a, 2014).

8.6 Conclusions

- As they follow different theoretical approaches, the Major Transitions Theory and the Operator Theory complement each other.
- The classes of the cell, the eukaryote cell and the multicellular are found in both approaches. Meanwhile, the class of the proto-cell is recognised only in Major Evolutionary Transitions theory, while the classes of the (prokaryote) multicellular, and of the neural network organism (the memon) occur exclusively in the Operator Theory.
- The Operator Theory suggests that the conventional use of the concept of multicellularity can be viewed as one large class that includes both pluricellular entities, based on physically attached cells, and multicellular organisms, the cells of which are connected through plasma strands. The 'multicellular condition' of single-celled protozoa is classified as a single-celled organism by the Operator Theory.
- In the wide scope of all possible major evolutionary transitions the Operator Theory identifies three classes of transitions with fundamentally different dynamics: transitions inside an organism (inward dimension, e.g., organs), transitions from one organism kind to the next (upward dimension, e.g., cell to multicellular), transitions from organisms to interaction systems (outward dimension, e.g., from plant to ecosystem, and from human being to society).

It is relevant that the Major Evolutionary Transitions theory is predominantly based on functional criteria, whilst the Operator Theory is based on the combination of structural and functional criteria. By adding structural criteria, the Operator Theory offers new pathways towards the creation of a stringent ontology for the classification of objects and transitions. In this chapter, one more step was set towards the goal of a general theory for individuality, transitions and levels of complexity, which integrates process and structure, and which can be applied both inside and outside biology.

References

Alvarez de Lorenzana JM (1993) The constructive universe and the evolutionary systems framework. In: Salthe SN (ed) Development and evolution. Complexity and change in biology. MIT Press, Cambridge, pp 291–308, Appendix

Bardele CF (1997) On the symbiotic origin of protists, their diversity, and their pivotal role in teaching systematic biology. Ital J Zool 64:107–113

Bonner JT (1974) On development: the biology of form. Harvard University Press, Cambridge, MA

Booth A (2014) Symbiosis, selection, and individuality. Biol Philos. doi:10.1007/s10539-014-9449-8

Bouchard F, Huneman P (eds) (2013) From groups to individuals. Evolution and emerging individuality. MIT Press, Cambridge, MA

Bourke AFG (2011) Principles of social evolution. Oxford University Press, Oxford

Buss LW (1987) The evolution of individuality. Princeton University Press, Princeton, NJ

Calcott B, Sterelny K (eds) (2011) The major transitions in evolution revisited. MIT Press, Cambridge, MA

Cartwright P (2013) Developmental insights into the origin of complex colonial hydrozoans. Integr Comp Biol 43:82–86

Chan CX, Bhattacharya D (2010) The origin of plastids. Nature Educ 3:84

Corning PA (1983) The synergism hypothesis. McGraw-Hill, New York

Corning PA, Szathmáry E (2015) 'Synergistic selection': a Darwinian frame for the evolution of complexity. J Theor Biol 371:45–58

Gagat P, Bodył A, Mackiewicz P, Stiller JW (2014) Tertiary plastid endosymbioses in dinoflagellates. In: Löffelhardt W (ed) Endosymbiosis. Springer, Wien, pp 233–290

Giddings TH, Staehelin LA (1978) Plasma membrane architecture of Anabaena cylindrica: occurrence of microplasmodesmata and changes associated with heterocyst development and the cell cycle. Cytobiology 16:235–249

Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford

Godfrey-Smith P (2013) Darwinian individuals. In: Bouchard F, Huneman P (eds) From groups to individuals. Evolution and emerging individuality. MIT Press, Cambridge, MA

Heylighen F (1990) Relational closure: a mathematical concept for distinction-making and complexity analysis. In: Trappl R (ed) Cybernetics and systems '90. World Science, Singapore, pp 335–342

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organisation of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2010a) The Operator Hierarchy, a chain of closures linking matter life and artificial intelligence, Alterra Scientific contributions 34. Alterra, Wageningen

Jagers op Akkerhuis GAJM (2010b) Towards a hierarchical definition of life, the organism, and death. Found Sci 15:245–262

Jagers op Akkerhuis GAJM (2012a) The pursuit of complexity. The utility of biodiversity from an evolutionary perspective. KNNV Publisher, Zeist, The Netherlands

Jagers op Akkerhuis GAJM (2012b) The role of logic and insight in the search for a definition of life. J Biomol Struct Dyn 29:619–620

Jagers op Akkerhuis GAJM (2014) General laws and centripetal science. Eur Rev 22:113–144

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego–bricks of nature: evolutionary transitions from fermions to neural networks. World Futures 53:329–345

Keeling PJ (2010) The endosymbiotic origin, diversification and fate of plastids. Philos Trans R Soc B 365:729–748

Koestler A (1978) Janus: a summing up. Hutchinson & Co. Ltd, London

Maynard Smith J (1988) Evolutionary progress and the levels of selection. In: Nitecki MH (ed) Evolutionary progress. University of Chicago Press, Chicago, pp 219–230

Maynard Smith J, Szathmáry E (1995) The major transitions in evolution. W.H. Freeman Spektrum, Oxford

McShea DW, Simpson CG (2011) The miscellaneous transitions in evolution. In: Sterelny K (ed) The major transitions in evolution revisited. MIT Press, Cambridge, MA

Miller JG (1978) Living systems. McGraw-Hill, New York

Pepper JW, Herron MD (2008) Does biology need an organism concept? Biol Rev 83:621–627

Queller DC, Strassmann JE (2009) Beyond society: the evolution of organismality. Philos Trans R Soc B 364:3143–3155

Salthe S (1985) Evolving hierarchical systems: their structure and representation. Columbia University Press, New York

Santelices B (1999) How many kinds of individual are there? Tree 14:152–155

Simon HA (1962) The architecture of complexity. Proc Am Soc Philos Sci 106:467–482

Stebbins G (1969) The basis of progressive evolution. University of North Carolina Press, Chapel Hill

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. Proc Natl Acad Sci U S A 112:10104–10111

Szathmáry E, Maynard Smith J (1995) The major evolutionary transitions. Nature 374:227–232

Turchin VE (1977) The phenomenon of science, a cybernetic approach to human evolution. Colombia University Press, New York

Von Bertalanffy L (1950) An outline of general system theory. Br J Philos Sci 1:134–165

West SA, Fisher RM, Gardner A, Kiers ET (2015) Major evolutionary transitions in individuality. Proc Natl Acad Sci U S A. doi:10.1073/pnas.1421402112

Chapter 9
In Defense of Gradualism

Jack Vromen

Abstract On the basis of his Operator Theory (OT), which stresses the requirement of dual closure, Jagers argues that all operators that are at least as complex as cells qualify as organisms. I argue that while this does indeed provide us with a set of clear and consistent criteria that unambiguously demarcate organisms from other things, it is hard to assess their adequacy because not much is said about the purpose(s) they are intended to serve. Without a specification of the latter, consistency and clarity as such may not count for much. I furthermore argue that if more traditional criteria of organismality are invoked—notably metabolism and reproduction—new scientific insights suggest that the gradualist school that Jagers rallies against makes more sense than Jagers is willing to grant. In some cases we might be forced to accept the fuzziness and ambiguity inherent in "degrees of organismality" that Jagers loathes. It is important to acknowledge that the fuzziness and ambiguity do not stem from vagueness in the list of criteria and in the meanings of the criteria that are invoked, but from the diversity and variety that we find in nature.

9.1 Comments

Suppose that one wants to arrive at a sensible list of criteria for organismality. How should one go about this? What criteria of adequacy should the list of criteria meet?

One way to go about this is to start with (what one takes or hopes to be) an incontrovertible complete list of organisms. The challenge is then to come up with criteria for organismality that jointly single out all the elements in this list. That is to say, the criteria should be such that all the things that meet the criteria belong to the list and all the things that do not meet the criteria do not belong to the list. Such criteria are called intentional demarcation criteria by Jagers and he states that searching for such criteria is a guiding principle for his Operator Theory OT.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_9

It might be instructive to dwell a bit longer on what this pathway implies. It presupposes that we already know what sorts of things qualify as organisms prior to, and independently of, explicitly specified criteria. If it is assumed that there is a coherent list of implicit criteria underneath this “pre-theoretic” classification, the task is to make the implicit criteria explicit. How do we know we have identified the right sort of criteria? By checking whether they sort out all organisms and by checking whether they sort out only organisms. Thus the antecedently identified list of organisms serves as the test bed here.

An altogether different, and indeed opposite, way to go about this is to allow for the possibility that there is no such incontrovertible complete list of organisms. Or it might be that we want to allow for the possibility that we do not know in advance with certainty which sorts of things should be on this list[1]. Perhaps this might be due to the fact that we are not sure what collection of criteria to invoke, either implicitly or explicitly. One way to cut the knot is here is to first clearly *stipulate* a few criteria and then to see what implications these have for the sorts of things we want to call organisms. A possible consequence of this strategy is that under the newly stipulated criteria some of the things that traditionally have been called organisms do not come out anymore as organisms.

Even though Jagers states that he is after intentional demarcation criteria (the first pathway discussed above), there is also textual evidence that he is traversing the second pathway. Indeed, if I had to put my money on this, I’d bet that Jagers ultimately favors the second strategy. There is nothing wrong with this. But it also raises a concern: How are we going to check or test in this second pathway whether the stipulated criteria are good ones? We cannot rely here on an antecedently specified complete list of organisms, as the recognition that we might lack such a list provides the very starting-point for this second pathway. What then can we rely on? This is not so clear here. It is clear that Jagers is looking for stipulative criteria that can be applied consistently and that lead to clear binary (all-or-nothing) decisions as to whether something is an organism. It seems Jagers wants to treat organismality like pregnancy: just as one cannot be a bit pregnant—one either is or isn’t pregnant—things cannot be bit organismal. As Jagers wants to see it, something either is an organism, or it isn’t an organism.

All this is fine. What we get is a clear and consistent set of criteria, derived from OT, leading to unequivocal decisions as to whether something is or isn’t an organism. But it also raises several questions. One such question is why we should adopt precisely the conditions proposed by Jagers. Why not different criteria? Arguably one of the reasons why the precise understanding of “organism” still is contested in biology is that many different criteria have been invoked to define organisms. Jagers argues that his criteria can settle this issue in a non-haphazard way. In Sect. 2.7.2 he discusses metabolism and reproduction as two of the more prominent traditional criteria for organismality. The first criterion states roughly that only those entities that have metabolism can be organisms. The second criterion states roughly that

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[1] I take it that this is what Jagers means when he argues (in $$ Sect. 2.7.2) that in the first approach the sorts of things to be included in the list are selected rather haphazardly.

only those entities that can reproduce can be called organisms. It is not just that these two criteria are very different and that it is not clear which one(s) should be picked, Jagers argues, it is also that the very notions of metabolism and reproduction are not clear in and by themselves. By contrast, the criteria proposed by OT are crystal clear and lead to unequivocal decisions as to whether something is an organism.

In Sect. 2.7.2 Jagers does not make clear how his own criteria relate to the traditional criteria of metabolism and reproduction[2]. What he does make clear (in Chap. 8) is that his own criteria are not just functional but also structural in kind. The notion of dual closure in OT implies both functional and structural criteria. He contrasts those with the purely functional criteria that are invoked in Major Evolutionary Transitions Theory (METT): cooperation, competition reduction, and reproduction as part of a larger unit. The problem with theories that solely use functional criteria, Jagers argues, is that structural differences between, for example, bees and colonies of bees and between cells in the slug of a slime mold and cells in a plant are disregarded. Whereas the cells in a plant are connected by plasma strands, the cells in the slug of a slime mold are not connected through plasma strands. That is why OT treats plants as (multicellular) organisms, while the slug of a slime mold is not an organism, but a pluricellular organization. Similarly, "… a bee represents a physically integrated unity that has a single body, whilst the colony is a result of behavioural interactions between many bees, each having a proper body"[3]. Thus, a bee is an organism, whereas a bee colony is not an organism, but an organization, or system, of interacting organisms.

Jagers argues that we need the addition of structural criteria to functional criteria to resolve the ambiguities in METT. I leave the issue of whether it is desirable to eliminate ambiguity for later. For the sake of argument I assume that that is desirable. But why should the additional criteria required be structural in kind? More in particular, why should the existence or non-existence of physical connections (via plasma strands for example) and of physical integration be decisive for the issue of whether or not to call something an organism? Why not something else? As far as I can see, Jagers does not give an answer. Throughout the book the generality of OT is praised. But is that enough to conclude that it can also render useful services for demarcating organisms from non-organisms? Or are these specific structural criteria invoked because they seem to bode well with "folk biology"? It is true that in the human eye a bee represents more of a physically integrated unity, having a single body, than a bee colony. But when we take more distance and zoom out on bees, colonies of bees (and flocks of birds for example) can also appear as a physically integrated unity with a single body. That's one of the reasons why they are sometimes called superorganisms. Conversely, when we zoom in on a bee we will also see many interactions between bee parts. Isn't it a bit arbitrary then to put forward physical connectedness and integration as the structural criteria to resolve ambiguities in METT?

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[2] The only thing he says about this is that "classical" criteria should be reconsidered in light of the criteria he advances.

[3] Remarks like these suggest that Jagers is talking more about biological individuality than about organismality.

I must admit I find it very hard to assess the adequacy of Jagers' criteria independently of what they are used for. What criteria should be invoked seem to me to be largely a matter of what we are interested in. The criteria that are appropriate for some purpose need not be appropriate for other purposes. Despite his enthusiasm for the generality of OT, Jagers does not seem to believe in all-purpose criteria either[4]. What specific purpose(s) are the structural and functional criteria derived from OT meant to serve? To what debate(s) do they contribute? Again, there is little in the text to draw on. But at some point (in Sect. 8.5.2) Jagers gives us some guidance. He argues that OT provides an innovative solution for the debate over the gradualist school. The gradualist school (Queller and Strassmann 2009; Godfrey-Smith 2009, 2013, 2014) holds that biological entities can exhibit various degrees of organismality: there might be clear cases of biological entities that are organisms for 100 % and biological entities that are organisms for 0 %, but there are also many cases in between.

It is instructive to quote Jagers at length here:

> The viewpoint of the gradualist school is not free of criticism. Specific objections are offered by Booth (2014) indicating that the utility of applying gradualism to a eukaryotic organism and its associated microbes, which together are also indicated as a holobiont, can be questioned because it offers no precise information about what kinds of causal interactions bind parts into interactors. Moreover, the conceptual payoff of discussing interactors, units of selection, or Darwinian individuals would not be clear if co-evolutionary approaches may already explain the origin of holobionts. In the light of such debate, the Operator Theory offers an innovative solution, by relating the organism concept strictly and only to any operator of the level of the cell and higher in the Operator Hierarchy (e.g., Jagers op Akkerhuis 2010b, 2012a, b). This simple definition indicates a precise range of kinds of operators which classify as organisms. Moreover, from an ontological perspective, the operator-based definition solves ambiguity because it allows a clear distinction between organisms, and systems of interacting organisms.

I am not sure whether I fully understand this[5]. But what transpires quite clearly, I think, is that Jagers believes OT can help us to get rid of the ambiguities implied by applying gradualism to holobionts. Instead of accepting that holobionts are organismal to a limited degree *x* (where $0\,\% < x < 100\,\%$), as gradualism supposedly does, OT insists that holobionts either are or aren't organisms.

As Booth (2014) explains, a holobiont is a collective composed of a macrobial organism and all of its associated microbes. There is growing recognition in biology that symbiotic relationships between macrobial organisms and their microbes are rather widespread in nature. Examples include the Aphid–*Buchnera* symbiosis and the squid–*Vibrio* symbiosis. These examples show that microbes inside macrobial organ-

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[4] As stated in personal communication.

[5] One of the things I do not understand is that Booth's critique targets the replicator–interactor framework. Godfrey-Smith, one of the spokesmen of gradualism, does not endorse this framework. In fact, Booth's second point, that coevolutionary approaches may already explain the origin of holobionts, draws on Godfrey-Smith's Darwinian population framework. More importantly, Booth seems to vindicate the sort of *pluralism* that Godfrey-Smith endorses: there are multiple options for understanding biologically relevant individuals. So it seems to me that Booth does not criticize the gradualist school at all.

isms are crucial parts of those organisms. They might be crucial not only for the macrobial organisms' metabolic purposes, but also for avoiding detection of the organisms by predators.

Note that this still does not answer the question of whether OT implies that holobionts are organisms or that it implies that holobionts are rather systems of interacting organisms. There is reason to believe that OT accepts that at least some holobionts are organisms. The reason is rather straightforward. Booth follows authors such as Dupré and O'Malley (2012a, b) in believing that we, as human bodies, are holobionts. As Booth argues, this belief has gained widespread acceptance in biology. And on Jagers' OT, since human bodies are operators, they are also organisms.

At the same time, Jagers rather categorically argues (in Sect. 2.8.2) that like the slug of a slime mold and a bee colony, symbiotic relationships cannot be called organisms. The reason is the same throughout: as the condition of structural closure is not met in these cases, these are not operators. Like the bees in the bee colony, the entities involved in symbiotic relationships can be organisms. But as wholes, symbiotic relationships cannot be organisms themselves.

Perhaps in cases like us, human bodies, Jagers would be prepared to accept that symbiotic ensembles can be organisms. Perhaps he would argue that the "… kinds of causal interactions" that bind microbial symbionts into human bodies are such that the structural criterion is met. But if so, he would have to concede at least that some symbiotic relationships can be organisms.

The intriguing features and implications of holobionts go further than this, however. It is clear that the microbes in the guts of our bodies play a crucial role in our metabolism. Indeed, they might be so important for this that they must be seen as indispensable parts in our metabolism. We thus are organisms not only comprising "familiar" human cells, but also microbes. Some of these microbes we "vertically" inherit from our biological parents. But others are picked up "horizontally" from the environment. If so, at least some parts of us belong to non-human evolutionary lineages. If the microbial symbionts were all vertically transmitted, one could conclude that the symbiotic whole both has metabolic autonomy and is a (collective) reproducer. In Godfrey-Smith's terminology, holobionts would then be organisms and Darwinian individuals. But if at least some of them are horizontally transmitted, as indeed it seems to be the case, then the criteria of metabolism and reproduction part ways. The "ensemble" (or "consortium") then does no longer reproduce as a unit. If so, human bodies are not Darwinian individuals (or at best marginal Darwinian individuals).

We could say that the criteria of metabolism and of reproduction draw attention to different dimensions of organismality. Adding a second criterion (say that of metabolism) need not result in delineating a proper subset of the set delineated by the first criterion (say that of reproduction). It might also be that adding a second criterion to a first criterion results in delineating a set that overlaps only partly with the set delineated by the first criterion. And instead of insisting that we should look at the intersection of the two sets, as Jagers seems to do with his structural and functional criteria, it might be more interesting to look at cases where the two sets do not overlap. The criteria might point in different directions so that all-or-nothing assessments of organismality are no longer possible. Things might be (or might be like) organisms in one respect, but not in another respect.

What is more, in each of these dimensions there might also be different degrees to which the criteria are met. Godfrey-Smith shows, convincingly in my opinion, that this holds for reproduction. Thus there can be paradigm cases of reproducers, but also marginal cases of reproducers (see also Vromen 2011). But this holds equally for metabolism. There might be various degrees to which the parts of a whole can survive when they are taken apart, for example. The more metabolic autonomy the parts have in this sense, the more organismal they are themselves. Godfrey-Smith (2013) points out that there is also an inverse relationship between the organismal degree of the parts and the organismal degree of the whole: the more organismal the whole is, the less organismal its parts. Thus we do not only have at least two different criteria for organismality, we also have different degrees of organismality with respect to each criterion.

A consequence of all this is that we indeed have to accept that we might have fuzzy boundary cases. Different things might indeed have different degrees of organismality. But I believe this is more illuminating things than it is blurring things (as Jagers seems to think). It is important to realize that the fuzziness and ambiguity in assessing organismality do not result from vagueness of the criteria invoked. They rather result from the often bizarre variety and diversity in nature itself. The gradualist school need not be, and actually isn't, motivated by some post-modern acceptance (or even endorsement) of fuzziness in representation. If anything, it is motivated by a modern confidence in progress in science: it takes new insights from biology about all the wondrous forms of life as facts of life.

References

Booth A (2014) Symbiosis, selection, and individuality. Biol Philos. doi:10.1007/s10539-014-9449-8

Dupré J, O'Malley MA (2012a) Size doesn't matter: towards a more inclusive philosophy of biology. In: Dupré J (ed) Processes of life: essays in the philosophy of biology. Oxford University Press, Oxford, pp 163–187

Dupré J, O'Malley MA (2012b) Varieties of living things: life at the intersection of lineage and metabolism. In: Dupré J (ed) Processes of life: essays in the philosophy of biology. Oxford University Press, Oxford, pp 206–229

Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford, UK

Godfrey-Smith P (2013) Darwinian individuals. In: Bouchard F, Huneman P (eds) From groups to individuals. Evolution and emerging individuality. MIT press, Cambridge, USA

Godfrey-Smith P (2014) Sender-receiver systems within and between organisms. Philos Science 81(5):866–878

Jagers op Akkerhuis GAJM (2010b) Towards a hierarchical definition of life, the organism, and death. Found of Science 15:245-262.

Jagers op Akkerhuis GAJM (2012a) The pursuit of complexity. The utility of biodiversity from an evolutionary perspective. KNNV Publisher.

Jagers op Akkerhuis GAJM (2012b) The Role of Logic and Insight in the Search for a Definition of Life. J Biomol Struct Dyn 29:619-620.

Queller DC, Strassmann JE (2009) Beyond society: the evolution of organismality. Phil Trans R Soc B 364:3143–3155

Vromen JJ (2011) Heterogeneous economic evolution: a different view on Darwinizing economics. In: Davis JB, Hands DW (eds) The Elgar companion to recent economic methodology. Edward Elgar, Cheltenham, pp 341–371

Chapter 10
The Role or Structural Criteria in Transition Theory: A Focus on Systems of Interacting Organisms

Gerard A.J.M. Jagers op Akkerhuis

> *"A herd of buffalo grows and then splits. Is that herd-level reproduction, or only buffalo level reproduction? If we say it is only buffalo-level reproduction, then why isn't this reductionist attitude applied to ourselves, leading us to say that the reproduction of a new human is merely a matter of cell-level reproduction along with a specific kind of organization of the cells? So here we encounter problems with the reduction of one set of entities to another, with how to think about levels of organization in nature, and again with individuality …"*
>
> (Godfrey- Smith 2009).

Abstract In a recent publication Szathmáry has updated Major Evolutionary Transitions theory to a version 2.0. The major transition theory recognises transitions based on the select use of functional criteria, notably: cooperation, competition reduction and reproduction as part of a larger unit. These criteria apply indiscriminatingly to cells forming a bee, and bees forming a hive. The possibility of suggesting different interpretations like these has caused ambiguity about the suitability of major evolutionary transitions as hallmarks for individuality or organismality. In this chapter it is suggested to deal with such ambiguity by the additional use of structural criteria when classifying transitions and resulting kinds of system. This chapter focuses on systems of interacting organisms, for which systems a decision tree is constructed that combines three different criteria to arrive at a classification. The decision tree starts with the fraternal and egalitarian interactions *sensu* Queller, adds democratic and centralised coding, and transcends the limitations of functional criteria by invoking the structural classes of the Operator Theory. These classes are operators (which applies to all organisms), compound objects and behavioural groups. If these additional criteria are used, one can resolve ambiguities about the classification of different kinds of groups of interacting organisms, such as pluricellular organisations, symbioses and groups.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_10

10.1 Introduction

Inspired by earlier studies, e.g. Stebbins (1969) and Buss (1987), Szathmáry and Maynard Smith (1995) have proposed Major Evolutionary Transitions theory. Recently, Szathmáry (2015) reviewed 20 years of development, and suggested updates towards a version 2.0 of the theory. The concept of a major evolutionary transition is related to functional criteria, notably cooperation, competition reduction and reproduction as part of a larger unit. While such functional criteria may offer necessary conditions for a specific transition, they do not always offer sufficient conditions. For example, the criteria of cooperation, competition reduction and of reproduction as part of a larger unit allow for groups that in different ways consist of cooperating objects. Accordingly, different kinds of transitions towards multicellularity can be recognised. For example Szathmáry (2015) refers to the slug of a slime mould as aggregative multicellularity, a plant and animal as cohesive multicellularity and to Lichen as egalitarian multicellularity. In an implicit way, the use of adjectives such as aggregative and cohesive indicate that all the examples represent different forms of multicellularity. From an ontological viewpoint it is an open question, however, whether or not all such groups of cells should be referred to as a multicellular organisations. It can be questioned, for example, whether or not Lichen really can be classified as multicellular organisms if the fungus involved is a multicellular organism that with its hyphae entangles individual algal cells, and when the algae can live separately whilst the fungus mostly cannot (Ahmadjian 1988; Sanders 2001). In this chapter it is demonstrated how the Operator Theory (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2001, 2008, 2012a) offers a way to deal with such puzzling cases, by using organisms as a basis for analysing different kinds of systems in which two or more organisms interact.

As a preparation for discussing systems of interacting organisms, one must necessarily start with defining the organism concept. In the past, it has been suggested that the functional criteria of cooperation, competition reduction and reproduction as part of a larger unit can be used for defining the organism concept. Based on functional criteria it has been suggested that both a queen bee and a colony of bees can be classified as organism (e.g. Wheeler 1911; Queller 2000, and Queller and Strassmann 2009). A colony has also been named a superorganism (Seeley 1989; Moritz and Southwick 1992). From the perspective of the Operator Theory, two aspects of a broad interpretation of the organism concept deserve attention. Firstly, viewing both bees and colonies as organisms is a source of ontological ambiguity, because in biology an organism is not supposed to have separate bodies (e.g. Metz 2013). If one aims at a consistent ontology, it may be wise to discourage the use of the term (super-) organism for groups of individually dwelling objects such as the bees of a bee colony. Instead of calling a beehive an organism, one can simply use the classical viewpoint that a beehive represents an organisation, a colony. Secondly, the assumption that the criteria for major transitions can be used for defining the organism concept can be viewed as the result of a chain of deductions that contains logical inconsistencies. Such a chain may start with a select list of functional criteria that are viewed as the hallmark of a major transition in biology. The selected criteria typically are: cooperation, competition reduction, and reproduction as part of a larger unit. Sometimes additional criteria are suggested, such as functional differentiation (Szathmáry and Maynard Smith 1995; Szathmáry 2015). These criteria match with several kinds of systems deemed organisms. The use of the term organism, however, is suggestive, because until this term has been defined explicitly, it can only be used in an intuitive way. Finally, from the observation that the criteria comply with some organisms, it is deduced that major transitions lead to organismality. A generalised conclusion based on this deduction is that all systems which result from a major evolutionary transition can be viewed as representing different kinds of organismality. The assumptions that underlay this line of reasoning can be summarised by the following analogy: because many birds can fly, the capacity to fly is what defines a bird.

To deal with the challenges in the above lines of reasoning, the current book suggests defining the organism concept with the help of the Operator Theory (short OT). As discussed in Jagers op Akkerhuis (2010b), Jagers op Akkerhuis (2012a, b), one can use the logic of the Operator Theory for defining the organism concept in two steps. Firstly, one defines the hierarchy of all the operators. Secondly, only the kinds of operators which are at least as complex as the cell are named organisms. These two steps allow the organism concept to be defined from the bottom up. According to this approach only the following kinds of organisation represent organisms:

- The kind of operator called a cell, which conventionally is referred to as a prokaryote.
- The kind of operator called a multicellular, such as blue-green algae.
- The kind of operator called an endosymbiont cell. This is conventionally called a eukaryotic cell. It is named differently by the Operator Theory, because of the persistence of the endosymbiont, while the karyos may dissolve during cell division.
- The kind of operator called an endosymbiont multicellular, such as a plant.
- The kind of operator called a memon. A momon is an organism with a special neural network with interface (see Fig. 2.3 in Sect. 2.6.2).
- In the future: technical memons.

The above classes demonstrate that the Operator Theory can provide a well-structured approach to defining the organism concept. With the definition of the organism as a basis, a next step can be made towards the definitions of different kinds of collectives of interacting organisms, e.g. a group, a symbiosis, a colony and a herd. In this chapter several criteria are explored that allow classifications of systems in which two or more organisms interact, which the Operator Theory refers to as interaction systems.

10.2 Outline

The preceding chapter of this book focusses on transitions that lead to the emergence of different kinds of organisms. In the current chapter the focus is on systems that result from interactions between organisms, while failing to classify as organisms. First it is explained how the Major Evolutionary Transitions theory and the Operator Theory deal with transitions towards groups of interacting organisms. With respect to the classification of interactions in such groups it was indicated by Queller (1997, 2000) and Queller and Strassmann (2009) that kinship is an important criterion. The current reasoning follows Queller in their suggestion of dividing the gradient of kinship relationships in two large parts: fraternal (high level of kinship) and egalitarian interactions (low level). In addition to kinship, two extra criteria are introduced with the aim of creating more specific classes. Consequences of the extra criteria are discussed, followed by a listing of conclusions.

10.3 Systems of Interacting Organisms in Major Evolutionary Transitions Theory and in the OT

In the following two paragraphs relationships are studied between the way Major Evolutionary Transitions theory and the Operator Theory deal with interactions between organisms and the new kinds of systems that result from such interactions.

10.3.1 Systems of Interacting Organisms in Major Evolutionary Transitions Theory

From the perspective of the Operator Theory, the following transitions listed in Szathmáry and Maynard Smith (1995) and Szathmáry (2015) (column 1 and 2 of Table 10.1) involve interactions between organisms:

- From asexual clones to sexual populations. This transition is listed in Maynard Smith and Szathmáry (1995). The subject is not included again in the listing of Szathmáry (2015).
- From solitary individuals to colonies. This transition corresponds with that towards eusocial animal societies in the listing of Szathmáry (2015).
- Societies with natural language. Szathmáry (2015) questions whether the transition from primate societies to human “eusociality” based on cooperation and language is a major transition. “The example is not, if one thinks in the context of multicellular organisms, termite mounds and beehives, but in another sense

Table 10.1 New units caused by interactions between organisms

Major transitions (original version) (1995)	Major transitions (version 2.0) (2015)	Operator hierarchy (1999–2016) Kind of operator involved in the major transition	Operator theory (2008–2016) Object of study is: – an operator – a compound obj. – a group	Operator Theory (2008-2016) Dimensions: – Upward dimension – Inward dimension – Outward dimension
		The physical attachment of cells, or of multicellulars, to colonies	Compound object: e.g. the pluricellular slug of a slime mould, a Lichen	Outward dimension: Change in interactive properties leads to a new kind of compound object
		Symbiotic relationships between non-attached organisms	Behavioural group	Outward dimension: Change in interactive properties leads to a new kind of group
Asexual clones to sexual populations		A specific kind of interaction between operators leads to the exchange of genetic information	Behavioural group	Outward dimension: Change in interactive properties leads to a new kind of group
Solitary individuals to colonies	Eusocial animal societies	Organisms with behaviour based on a neural network	Behavioural group	Outward dimension: Change in interactive properties leads to a new kind of group
Primate societies to human societies	Societies with natural language	Organisms with behaviour based on a neural network	Behavioural group	Outward dimension: Change in interactive properties leads to a new kind of group

Relationships between the major evolutionary transitions as proposed by (Szathmáry and Maynard Smith 1995) (column 1 and 2) and the Operator Theory as proposed by (Jagers op Akkerhuis and van Straalen (1999) (column 3 to 5). *Shading* in the rightmost column indicates the outward dimension (*dark grey*) of the Operator Theory. A complete Table of transitions towards operators and interaction systems can be found in Appendix)

> the answer is … affirmative" (Szathmáry 2015, p 6). Szathmáry (2015) adds that the affirmation is supported by the presence of key elements of evolutionary transitions: "cooperation (including reproductive levelling and food sharing), a form of eu-sociality, a powerful novel inheritance system, and living in groups." It is seen as a confirmation of competition reduction that "Due to social care (including medicine) and agriculture, the biology of humans has become gradually de-Darwinised."

Additionally Szathmáry (2015, Fig. S2) introduces a quadrant for different examples of multicellularity, which is based on two dimensions: (1) egalitarian or fraternal origins, (2) cohesive or aggregative origins. The examples in this quadrant are all viewed as multicellular units. In the discussion section special attention is paid to the question of whether or not all such examples can be gathered indiscriminatingly while using the umbrella concept of multicellularity.

10.3.2 Systems of Interacting Organisms in the Operator Theory

In the preceding section the discussions focused on the Major Evolutionary Transitions theory and how it identifies major transitions that lead to systems consisting of interacting objects. Such major transitions are now related to the Operator Theory. As explained in Chap. 2 the Operator Theory first defines all the operators and their hierarchy, and subsequently uses this information as a basis for analysing systems of interacting operators. Any system that is not an operator is viewed by the Operator Theory as an interaction system (Jagers op Akkerhuis 2008, 2010a, 2014). Inside the class of interaction systems one can find various subgroups, for example the mutually excluding classes of compound object and behavioural group (see Fig. 2.4 Sect. 2.6.2).

10.4 An Integrated Approach to the Classification of Compound Objects and Groups

In the preceding chapter, an overview is offered of how the Major Evolutionary Transition theory and the Operator Theory classify systems that consist of interacting organisms, and that are not organisms themselves. As an addition to this field, the goal of this chapter is to offer a classification scheme that is based on the following three criteria.

The first criterion follows Queller (1997) who focuses on the genetic similarity of interacting organisms, as expressed by the level of kinship. When the interacting organisms show a high level of kinship, for example when they are offspring of the same parent, or belong to the same species, their interaction is named fraternal. Interactions between organisms with a low level of kinship, e.g. organisms of different species or higher taxonomic classes, are named egalitarian. The criterion of kinship creates a link to the well-known theory of kin selection (e.g. Hamilton 1964a, b).

The second criterion that is used here focuses on two major causes of kinship which will be referred to as: centralised coding and democratic coding. Centralised coding implies that a single individual has a high level of control over the genetics of all the members of the group. The organisms in the group are in principle all offspring of the same parent, such as clonal adhering cells of primitive algae, or the worker bees in a bee colony. Democratic coding implies that organisms in the group must not be the offspring of a single parent and accordingly have relatively independent or mixed genetic backgrounds, such as the cells in the slug of a slime mould, or a school of fish.

The third criterion is based on the three major kinds of structural organisation that are recognised by the Operator Theory (which were introduced in Sect. 2.7.3):

(1) organisms or other operators, (2) compound objects, and (3) groups. This third criterion is added with the aim of resolving ontological ambiguities, such as may arise through the select use of functional criteria. For example Queller and Strassmann (2009) suggest that near conflict-free cooperation is a sufficient criterion for classifying an organisation as an organism. According to this viewpoint, any colony that has conflict-free cooperation, such as a social insect colony, can be viewed as an organism. This ambiguity between organisms and colonies can be solved by the use of structural criteria offered by the Operator Theory. From the perspective of the Operator Theory it would violate a fundamental distinction between operators/organisms on the one hand and interaction systems on the other if a colony is viewed as an organism. The following paragraphs explore how the combination of the above three criteria can form the basis for a classification of kinds of interactions between organisms.

10.5 Fraternal Interactions ("Like" Organisms)

In this chapter, a classification is suggested that is based on three criteria: fraternal/egalitarian interactions, centralised or democratic coding and the structural criteria of the Operator Theory. Figure 10.1 offers an overview of the classification that is the product of these three steps.

10.5.1 Fraternal Interactions Based on Centralised Coding

This chapter focuses on interactions between groups of "like" organisms. It may seem strange in this context, that the scheme of Fig. 10.1 includes a developmental history. However, a developmental history can be viewed as a programmed pathway through various stages (Fig. 6.3), some of which are organisms, e.g. a zygote, while others are groups of interacting organisms. For example until the early eight cell stage a human being (see the classification in Sect. 8.4) consists of loosely attached cells, and classifies as a group. The development through different stages of the human embryo is coded for by genes and other information (e.g. plasmatic information) in the zygote, whose offspring can be viewed as a clone. As has been indicated for example by Grosberg and Strathmann (2007), Wheeler (1911), West et al. (2015) the coding in the founding zygote determines how the members of the offspring-clone in interaction produce developmental histories of differing complexity.

A primitive developmental history may stop at the compound object stage. An example is algal pluricellularity, where multiple cells form an aggregate, without that plasma connections are formed. Algal pluricellularity can be found for example in the *Tetrabaenaceae* (for example *Basichlamys* or *Tetrabaena*). In these taxa four celled states can be found, the cells of which are kept together through a common extracellular matrix, or through attachment to a parental sac. A review by Nozaki

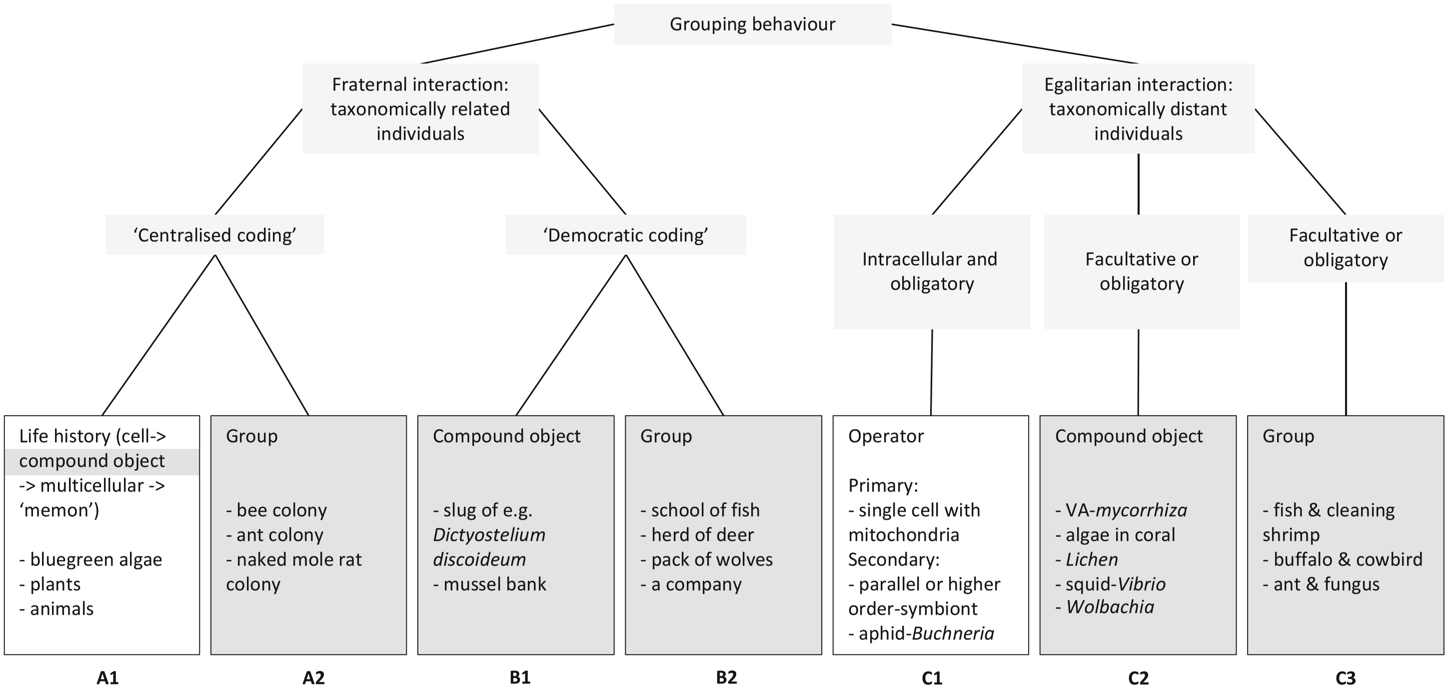

Fig. 10.1 Different kinds of grouping behaviours of organisms, and how these behaviours can lead to the formation of groups, compound objects and higher-level organisms. *Dark grey shading*: interaction systems of the kind compound object or group. *White shading*: organisms or developmental history leading to organisms

(1996) shows that no plasma strands are formed between such cells and that each cell in the quartet is capable of independent asexual reproduction. Typically, plasma connections are found only in the larger, more advanced species of algae (Nozaki et al. 1996).

A more complex developmental history can pass through many different stages, which may or may not represent an organism. For example in humans, the zygote (a single cell) develops to the 2, 4, and 8 cell stage (all representing colonies), to the late 8 cell stage (multicellular as soon as plasma connections are formed between the cells), to the morula, the blastula (multicellular), and finally to an organism with a neural network. According to the Operator Theory an organism with a hypercyclic neural network with an interface of sensors represents a higher level organism called memon, which concept was introduced to prevent confusion about unicellular and multicellular animals (Jagers op Akkerhuis 2010b).

After selection for a strong centralised coding as the basis of a developmental history, such coding allows for interesting extensions of the rule that a developmental history starts with clonal division of a single cell. For example, if two human zygotes that originate from the same female clump together, and form a mixed two cell colony, their programming is so similar that the pair of cells can still develop into a single human being, called a *chimera*, that has some tissues/organs that are genetically different from other tissues/organs because their cells descended from different zygotes.

Centralised coding also stands at the basis of eusocial colonies of for example honey bees, ants and naked mole rats (Fig. 10.1-A2). In principle, eusocial colonies form when a single reproducing individual, e.g. a queen bee, gives birth to non-reproducing offspring that become helpers. The queen bee indirectly "programmes" the behaviour of the worker bees, via the pathway that leads from her genes (and those of the drone(s) she mated with) to her eggs, to the wiring of the brains of her offspring, to the reflexes based on this wiring, to the behavioural repertoire based on these reflexes. The behavioural repertoire makes the worker bees feed the queen, construct hives, feed the larvae, search for nectar, etc. As the worker bees have a common descent from the queen, and lack the ability to reproduce, they can be viewed as the flying interface of the queen. The quality of the flying interface determines a queen's fitness. If the genetic coding by the queen fails, her worker bees will not behave well, resulting in a dysfunctional colony. A queen with a dysfunctional colony will experience selective disadvantage in comparison to queens with colonies that function properly. Meanwhile, the Operator theory classifies a queen bee as an organism, while the colony classifies as a group of organisms.

After evolution has selected for strong colonial group-behaviour, this can form the basis for a colony with a chimeric organisation. Chimeric colonies can form when two colonies merge after queen loss (Kronauer et al. 2010) or when ants steal pupae of other colonies to make slaves, as observed in various species in the *Formica sanguinea* group (Ruano et al. 2013).

10.5.2 Fraternal Interactions Based on Democratic Coding

Democratic coding implies that the reproducing organisms in the group are not necessarily genetically uniform. A typical example of fraternal interactions that result from democratic coding is the slug of the cellular slime mould *Dictyostelium discoideum* (Fig. 10.1-B1). Cells of this species generally live and reproduce as individuals. When food becomes scarce, the genes for aggregative behaviour are turned on, and the individuals aggregate and form a slug-like structure. This slug-like structure forms the starting point for cell differentiation and sexual reproduction. As the cells are not connected through plasma strands, the Operator Theory classifies the slug-like structure as a compound object (not as an operator/organism). Another compound object which is the result of democratic coding is that of the parasitic male anglerfish which fuses its skin and blood vessels with the female. The female and male can still be recognised (structurally) as separate animals (and thus as separate organisms) as long as each individual retains its proper neural network.

Democratic coding in combination with learning can lead to the formation of organised groups of organisms of the same species, e.g. herds of deer, packs of wolves, schools of fish and companies (Fig. 10.1-B2). In such groups, the coding for behavioural reflexes, the coding for a brain with the capacity to learn social habits, and the actual learning of social habits from peer organisms can go hand in hand. As soon as acquired/learned properties can be transferred between individuals, the focus of evolutionary analyses must split. In addition to the pattern of genetic Darwinian evolution of the organisms over generations, one must now also take into account the pattern of Darwinian evolution of the transferred properties within a generation. If an organism can learn, nature (genetics) and nurture (learning) will require a dual inheritance theory (Henrich and McElreath 2007). Ideas or habits that can be learned through imitation have also been studied under the name of memes (Blackmore 1999; Buskes 2013; Dawkins 1976).

Examples of groups in society that primarily are based on learned behaviours are for example companies, religions, political parties, families and football teams. An individual can choose to be a member of different groups at the same time, or at different moments, and is not physically attached to the group. Accordingly, the Operator Theory classifies a behavioural group as a group, not as an organism or compound object.

10.6 Egalitarian Interactions ("Unlike" Organisms)

Egalitarian interactions involve individuals of taxa which are not closely related. Here it is explained how egalitarian interactions can form the basis for new organisms, for compound objects and for behavioural groups.

10.6.1 Egalitarian Interactions That Produce a More Complex Organism

An example of an egalitarian interaction representing a new organism is the obligatory endosymbiont relationship which may evolve from facultative symbiosis of taxonomically unrelated individuals (Fig. 10.1-C1). In all cases where the endosymbiont cell(s) reside inside the membrane of the host cell (structural closure) and the host and endosymbiont depend obligatorily on each other (functional closure), the Operator Theory views the result as an organism because the obligatory mutual dependency and the containment comply with dual closure, which is the hallmark of a new level of organisation in the Operator Theory. As a consequence of dual closure, both the endosymbionts and the host cell must reproduce together, through singular vertical transmission.

There are many examples of obligatory endosymbiont organisations, such as the mitochondria in protozoa, fungi and animals, the mitochondria and chloroplasts in plants and algae, the interaction between aphids and the bacteria *Buchnera aphidicola,* and some obligatory interactions between *Wolbachia* bacteria and their host. In the example of aphids, the Buchneria bacterium synthesises essential amino acids for the aphid (Brinza et al. 2009). The obligatory symbiosis is sustained upon reproduction, because the bacterium is transferred vertically inside the ovum. As the aphid already inherited mitochondria from its unicellular ancestors, this obligatory cooperation represents a late evolutionary secondarily acquired endosymbiosis. In the case of Wolbachia, interactions can range from parasitic, to mutually and obligatorily symbiotic. Only the latter kind of interactions complies with dual closure and classifies as an organism.

10.6.2 Egalitarian Interactions That Produce a Compound Object

Egalitarian interactions can lead to new forms of organisms, and can also lead to the formation of compound objects (Fig. 10.1-C2). In a compound object the organisms are structurally more strongly attached to each other than to their environment and can be displaced together. For example, when a plant with *vascular arbuscular mycorrhizae* is uprooted, and replanted somewhere else, the fugal hyphae that grow in the roots, and protrude into the cells with so called arbuscules, must move with the plant. Similarly, symbiotic algae may live inside the cells of tissues of corals, in a facultative relationship, and will generally be transported together with the coral polyps. And in a Lichen, the fungal and algal component move together as the result of their interwoven structure. Such interwoven structures may split of parts that become next generation objects while the algae and fungus evolve symbiotically (Sanders 2001). Another example is the squid–*Vibrio* interaction. Young squids acquire the *Vibrio* bacteria from sea water. The bacteria grow in special cavities of the squid's body, and move along with the squid.

In all the above examples no plasma connections have been demonstrated between individuals of the two species, for which reason the interactions represent compound objects. Finally, there exist many host–parasite interactions that represent compound objects. An example is the existence of for example tapeworms in human intestines, or malaria parasites in human tissues. While being part of the egalitarian compound object, the individuals of both species continue to reproduce as representatives of two different phylogenetic taxa, and classify as a co-evolutionary relationship for this reason.

10.6.3 Egalitarian Interactions Resulting in the Formation of a Group

Interactions between taxonomically unrelated individuals can also lead to the formation of groups of interacting organisms (Fig. 10.1-C3). An example of a group-wise interaction is that of fish which let themselves be cleaned by shrimps that live on coral reefs. Another example is that of cowbirds feeding on small insects and other material from the skin of buffalo. An obligatory form of a symbiotic interaction between two species is that between fungus-growing ants (of the tribe *Attini*) and the fungus they rear in chambers in their burrows.

10.7 Discussion

In the introduction, it was explained that the Major Evolutionary Transitions theory selectively uses functional criteria that match with a broad range of different kinds of transitions and systems. It was furthermore indicated that while the functional criteria of Major Evolutionary Transitions theory have a broad validity, they lack a structural component. The author of this text now claims that a structural component is required both for the distinction between specific kinds of transitions and for the construction of a stringent classification of different kinds of systems of interacting organisms. This is the reason why it is explored whether the classification of the Major Evolutionary Transitions theory can be made more specific by the introduction of structural criteria. Following this addition, a decision tree for systems of interacting organism was developed which integrates functional criteria and structural criteria (Fig. 10.1). Through the combination of functional and structural criteria, steps are set in the direction of a general classification of transitions in biology. In the following chapters various aspects of this general classification are discussed.

10.7.1 Comparing the Classifications of Major Evolutionary Transitions Theory and the OT

Table 10.1 relates the different ways how the Major Evolutionary Transitions theory and the Operator Theory think about systems of interacting organisms. Examples in Maynard Smith and Szathmáry (1995) of transitions that lead to systems of interacting organisms are: the transition from clones to sexual populations, the transition from solitary individuals to colonies, and the transition from primate societies to human societies (Table 10.1, column 1). Examples in Szathmáry (2015) are: eusocial animal societies, and societies with natural language (Table 10.1, column 2).

According to the viewpoint of the Operator Theory, the major evolutionary transitions that were just discussed are based on new ways of how individuals interact in a group. For example, if a new behaviour emerges that stimulates the individuals to exchange genetic material, such behaviour causes a transition from an asexual group to a sexual group. And a change in the genetically programmed aspects of behaviour that stimulate individuals in a group to cooperate can form the basis for eusocial animal colonies. Finally in an already existing primate society, the gradual improvement of the means of verbal communication (from sounds to language) may lead to a transition to a language based society. As is indicated in Table 10.1, these three transitions are all viewed by the Operator Theory as examples of transitions along the outward dimension, and are based on new means of interacting between the objects that are being viewed as belonging to the group.

In addition to the above three major transitions of Maynard Smith and Szathmáry (1995), the Operator Theory suggests two more examples. One example is the case were separately dwelling organisms of different species interact in a symbiotic way. For example a crocodile may open its mouth to let a bird clean its teeth. And a second kind of interaction which is not included in the Major Evolutionary Transitions theory is that of cells, or of multicellular organisms, which attach to form a larger unit, while the unit does not classify as an organism, but as a compound object/colony.

Finally it is interesting to observe how the Major Evolutionary Transitions theory itself reflects on the criteria that it has suggested for the identification of major transitions. An illustrative example is offered by the way that Szathmáry (2015) answers the question of whether or not the case of human sociality represents a major transition, and suggests that one can speak of a major transition because: “We see key elements that are highlighted in other transitions: cooperation (including reproductive levelling and food sharing), a form of eusociality, a powerful novel inheritance system, and living in groups”. It is added that: “Due to social care (including medicine) and agriculture, the biology of humans has become gradually de-Darwinised.” This argumentation suggests that it is aimed at a very general use of the concept of the major evolutionary transitions, by extending the set of criteria to include for example social care, medication, a novel inheritance system and agriculture. While the functional criteria that were used for the identification of a major transition, e.g. cooperation, competition reduction and reproduction as part of a larger unit already fitted to a broad range of different kinds of systems, the additional inclusion of criteria such as social care, medication and agriculture may reduce the filtering role of criteria for major transitions further still.

10.7.2 (De) Coupling Organismality and Multicellularity

As the study of Szathmáry (2015) suggests, the Major Evolutionary Transitions theory views multicellularity as a condition that is the result of either aggregative or cohesive interactions, while “In the life cycle, the multicellular condition arises either by cells (or nuclei) coming together, or by cell division, followed by sticking together.” Examples offered of the multicellular condition are: “some eubacteria, two kinds of cellular slime moulds, and some ciliates” (Szathmáry 2015). Based on such reasoning, several different kinds of grouped cells are classified as a multicellular organism. For example the slugs of slime moulds are classified as aggregative multicellularity, plants and animals as cohesive multicellularity and Lichens as egalitarian multicellularity (Szathmáry 2015). This way of using adjectives presumes that each of the examples has the multicellular condition. In addition to this, it can be concluded from the following citations, that the multicellular condition is also viewed as a sufficient criterion for the entity to be classified as an organism: “Certain cases of symbiosis sit rather comfortably in the organism category, despite the fact that their egalitarian nature precludes reproductive division of labor…” (Szathmáry 2015). Apparently, the capacity of the algae to reproduce independently (Sanders 2001) is not viewed as an obstacle for classifying Lichens as organisms because “Ultimately what allows organism formation from lower level units is a high level of cooperation and a low level of realized conflicts” (Szathmáry 2015).

As the above citations indicate, the Major Evolutionary Transitions theory suggests that many kinds of groups of cells can be viewed as representing different forms of multicellularity, and as representing an organism. The Operator Theory now suggests several additions to this viewpoint. Importantly, the Operator Theory views the multicellular condition as a broad class, which can be subdivided into different kinds of organisation. One subclass would be the class of multicellular organisms. According to the viewpoint of the Operator Theory the presence of plasma connections between the cells is a necessary criterion for a group of cells to be classified as a multicellular organism. Consequently, the Operator Theory classifies the slug of a slime mould as a pluricellular organisation (which is not an organism) of the kind compound object (see Fig. 10.1) because the cells lack plasma connections. Where Szathmáry (2015) unifies all groups of cells using the concept of the multicellular condition, the viewpoint of the Operator Theory would be that in order to prevent confusion, it may be practical to distinguish between a multicellular condition, and a pluricellular condition. The multicellular condition is typical for a multicellular organism. The pluricellular condition is typical for a pluricellular organisation.

The example of multicellularity is discussed in detail, because it illustrates clearly several important differences between the school of Major Evolutionary

Transitions theory, and the Operator Theory. Such differences are also relevant for the way Szathmáry (2015, Fig. S2) organises different origins of multicellularity in a quadrant based on the following two dimensions: (1) fraternal or egalitarian origins, (2) cohesive or aggregative origins.

With respect to the treatment of cohesive or aggregative origins of fraternal interactions, the approach of Szathmáry (2015) shows close correspondence with Fig. 10.1 and how this is organised according to centralised/democratic coding. The evolution of the cohesive route can be thought of as being scaffolded by centralised coding. The evolution of the aggregative route can be thought of as being scaffolded by democratic coding. The route from democratic coding to multicellularity suffers from genetic limitations which stand in the way of interactions to develop beyond mere aggregation.

The Operator Theory now adds to this, that the situation is more complicated. The reason is that cohesive fraternal interactions can lead to different kinds of entities that consist of multiple cells. To explain how two kinds of algal groups consisting of multiple cells can emerge through the cohesive route of Szathmáry (2015, Fig. S2, transition 14-18), the developmental history of primitive group-forming algae can serve as an example. Interestingly, in some algae the cohesion leads to a group of clonal cells (which lack plasma connections), while in other algae the integration continues with the formation of plasma connections, which according to the Operator Theory implies a transition towards a multicellular organism. This example demonstrates that cohesion alone is not a decisive criterion for the development towards either a pluricellular or a multicellular form of organisation. In accordance with this, the Operator Theory holds a synchronic perspective on organisational states, which results in a focus on the momentary kind of organisation. This leads to the recognition that both the pluricellular form and the multicellular form may occur in sequence during a cohesion event that is part of a developmental trajectory.

And due to the lack of plasma connections between the cells, the Operator Theory holds a different view on the classification of Szathmáry (2015) of the slug of a slime mould as an example of fraternal aggregative multicellularity (Fig. S2, transition 15 to 19). Even though the slug of a slime mould consists of multiple cells, these cells are not connected via plasma strands. For this reason the Operator Theory does not classify the slug as a multicellular organism, but as a pluricellular compound object.

We now switch in the quadrant of Szathmáry to egalitarian interactions of cohesive and aggregative origin. The author of this chapter could not make out from Fig. S2 of Szathmáry (2015) whether this also includes the egalitarian interaction that leads to the protist host-cell with obligatory endosymbionts. According to the logic of the Operator Theory the construction of a cell with one or more obligatory endosymbiont(s) represents an interaction between multiple cells, while at the same time the overall system is viewed as representing a single-celled endosymbiont, and is not viewed as a multicellular. The reason is that the obligatory interactions between the host cell and the endosymbiont cell, and the obligate encapsulation of the endosymbiont by the host, represent dual closure, and are viewed for this reason as a singular unity, an organism, of the endosymbiont kind. The moment that dual closure is realised, the ontological status of a cell inside the endosymbiont is changed from a cell, to an acquired cellular organelle.

Presumably, the examples of Lichens and the squid–Vibrio symbiosis also belong to the egalitarian part of the quadrant of Szathmáry. However, where the Fig. S2 of Szathmáry (2015) includes different forms of multicellularity as if these represent organisms, the Operator Theory views for example the Lichen and the squid–Vibrio symbiosis as a compound object (e.g. Lichens, class C2 in Fig. 10.1). These examples demonstrate that by adding the structural viewpoint of the Operator Theory, new light can be shed on the classifications used by the Major Evolutionary Transition theory.

10.8 Conclusions

In this book the Major Evolutionary Transitions theory and the Operator Theory are related while focusing on transitions that lead to systems of interacting organisms without that such interactions represent a new organism. Such systems are called interaction systems by the Operator Theory, which theory also indicates that the class of the interaction systems can be subdivided into two mutually excluding subclasses: compound objects and behavioural groups (see Chap. 2).

If one uses the classification of the Operator Theory, which is based on organisms and other operators, on compound objects, and on behavioural groups, this offers new possibilities for the classification of major evolutionary transitions. For example, the transition towards multicellularity no longer applies to any and all systems in which attached cells cooperate, show reduced competition and reproduce as part of the larger unit. In all examples where the cells are attached but not connected through plasma strands, e.g. the slug of a slime mould, and Lichens, the interactions result in a pluricellular compound object, instead of forming a multicellular. And a protist with endosymbiont mitochondria classifies as a single celled organism, instead of as a multicellular organism. The reason is that Operator Theory views multicellularity as a form of organisation which involves interactions between adjoining cells, instead of between interior cells. Such differences demonstrate that the Operator Theory adds important new insights to the Major Evolutionary Transitions theory (Szathmáry 2015). Such additional insights were discovered because the Operator Theory aims at solving conceptual ambiguities that result from a select use of functional criteria. One kind of ambiguity is that Major Evolutionary Transitions theory allows for different kinds of organisation to being grouped as multicellular, such as aggregative multicellularity (the slug of a slime mould), cohesive multicellularity (a plant or animal) and egalitarian multicellularity (e.g. unicellular protists, the Buchneria–aphid symbiosis, Lichens and some plant–pollinator pairs). Another kind of ambiguity is that the very general functional criteria of the Major Evolutionary Transitions theory (e.g. cooperation, competition reduction and reproduction as part of a larger unit) are sometimes used as a hallmark for whether or not an entity is an organism. Accordingly, both a bee and a eusocial colony can be viewed as an organism, which represents an ontologically ambiguous situation. Solving the latter ambiguity, the Operator Theory classifies bees as organisms, and a colony of bees as a behavioural group.

The relationships between the Major Evolutionary Transitions theory and the Operator Theory indicate that the Operator Theory is at the same time less and more ambitious in its goals. The Operator Theory is less ambitious, because the concept of dual closure does not aim at explaining a broad range of transitions, but only those transitions that lead from one kind of operator to the next. At the same time, the Operator Theory is more ambitious, because it envisions a stringent ranking of all the kinds of operators, and transitions, in a meta-framework, such that every single transition and system kind has its proper position in the framework. Another ambition of the Operator Theory is to describe physical systems which are not operators as the product of interactions between operators.

McShea and Simpson (2001) have compared viewpoints on major transitions in evolution by Huxley (1942), Maynard Smith (1988), Maynard Smith and Szathmáry (1995), Stebbins (1969). In their "afterthoughts" they conclude that: "There is something philosophically muddled and scientifically casual about these three treatments of evolution at the largest scale", and that "The goal of finding a unity in that history hovers above evolutionary discourse as the moon once did above the Earth, inviting the bold to explore the limits of what we can know and learn." While a new paradigm such as the Operator Theory always requires thorough investigation, the introduction of the operator concept, and the ranking of all the kinds of operators in the operator hierarchy, may potentially offer an interesting step forward towards a unified theory of individuality, organisational kinds and hierarchical transitions in biology and nature.

References

Ahmadjian V (1988) The lichen alga Trebouxia: does it occur free-living? Plant Syst Evol 158:243–247

Blackmore S (1999) The meme machine. Oxford University Press, Oxford, UK

Brinza L, Viñuelas J, Cottret L, Calevro F, Rahbé Y, Febvay G, Duport G, Colella S, Rabatel A, Gautier C, Fayard J-M, Sagot M-F, Charles H (2009) Systemic analysis of the symbiotic function of Buchnera aphidicola, the primary endosymbiont of the pea aphid Acyrthosiphon pisum. C R Biol 332:1034–1049

Buskes C (2013) Darwinism extended: a survey of how the idea of cultural evolution evolved. Philosophia. Available at http://link.springer.com/article/10.1007%2Fs11406-013-9415-8#

Buss LW (1987) The evolution of individuality. Princeton University Press, Princeton, NJ

Dawkins R (1976) The selfish gene. Oxford University Press, Oxford

Grosberg RK, Strathmann RR (2007) The evolution of multicellularity: a minor major transition? Annu Rev Ecol Evol Syst 38:621–654

Hamilton W (1964a) The genetical evolution of social behaviour I. J Theor Biol 7:1–16

Hamilton W (1964b) The genetical evolution of social behaviour II. J Theor Biol 7:17–52

Henrich J, McElreath R (2007) Dual inheritance theory: the evolution of human cultural capacities and cultural evolution. In: Dunbar R, Barrett L (eds) Oxford handbook of evolutionary psychology. Oxford University Press, Oxford, pp 555–570

Huxley J (1942) Evolution in action. Harper, New York

Jagers op Akkerhuis GAJM (2001) Extrapolating a hierarchy of building block systems towards future neural network organisms. Acta Biotheor 49:171–189

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organisation of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2010) Towards a hierarchical definition of life, the organism, and death. Found Sci 15:245–262

Jagers op Akkerhuis GAJM (2010a) The Operator Hierarchy, a chain of closures linking matter life and artificial intelligence. Alterra Scientific 34

Jagers op Akkerhuis GAJM (2012a) The pursuit of complexity. The utility of biodiversity from an evolutionary perspective. KNNV

Jagers op Akkerhuis GAJM (2012) The role of logic and insight in the search for a definition of life. J Biomol Struct Dyn 29:619–620

Jagers op Akkerhuis GAJM (2014) General laws and centripetal science. Eur Rev 22:113–144

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego–bricks of nature: evolutionary transitions from fermions to neural networks. World Futures 53:329–345

Kronauer DJC, Schöning C, d'Ettorre P, Boomsma JJ (2010) Colony fusion and worker reproduction after queen loss in army ants. Proc R Soc B 277:755–763

Maynard Smith J (1988) Evolutionary progress and the levels of selection. In: Nitecki MH Evolutionary progress. Univ of Chicago Press, Chicago, pp 219–230

Maynard Smith J, Szathmáry E (1995) The major transitions in evolution. W.H. Freeman Spektrum, Oxford

McShea DW (2001) The minor transitions in hierarchical evolution and the question of a directional bias. J Evol Biol 14:502–518

Metz JAJ (2013) On the concept of individual in ecology and evolution. J Math Biol 66:635–647

Moritz RFA, Southwick EE (1992) Bees as superorganisms: an evolutionary reality. Springer, Berlin

Nozaki H, Itoh M, Watanabe MM, Kuroiwa T (1996) Ultrastructure of the vegetative colonies and systematic position of *Basichlamys (Volvocales, Chlorophyta)*. Eur J Phycol 31:67–72

Queller DC (1997) Cooperators since life began. Review of: Maynard Smith J, Szathmáry E, the major transitions in evolution. Q Rev Biol 72:184–188

Queller JW (2000) Relatedness and the fraternal major transitions. Philos Trans R Soc Lond B Biol Sci 355:1647–1655

Queller DC, Strassmann JE (2009) Beyond society: the evolution of organismality. Philos Trans R Soc Lond B Biol Sci 364:3143–3155

Ruano F, Sanllorente O, Lenoir A, Tinaut A (2013) Rossomyrmex, the slave-maker ants from the arid steppe environments. Psyche 2013:1–7

Sanders WB (2001) Lichens: the interface between mycology and plant morphology. Bioscience 51:1025–1036

Seeley TD (1989) The honey bee colony as a superorganism. Am Sci 77:546–553

Stebbins GL (1969) The basis of progressive evolution. University of North Carolina Press, Chapel Hill

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. PNAS 112:10104–10111

Szathmáry E, Maynard Smith J (1995) The major evolutionary transitions. Nature 374:227–232

West SA, Fisher RM, Gardner A, Kiers ET (2015) Major evolutionary transitions in individuality Proc Natl Acad Sci U S A. doi: 10.1073/pnas.1421402112

Wheeler WM (1911) The ant colony as organism. J Morphol 22:307–325

Chapter 11
Major Transitions, Operator Theory, and Human Organization

Jan-Willem Stoelhorst

Abstract This comment contrasts the axiomatic treatment of transitions in Operator Theory with the more inductive and descriptive treatment of transitions in Major Evolutionary Transitions Theory. I conclude that Operator Theory demonstrates the need for, and the possibility of, a much finer-grained analysis of major transitions than Major Evolutionary Transitions Theory currently offers.

11.1 Introduction

"Operator Theory" (OT) as developed by Jagers op Akkerhuis raises many interesting issues that warrant further discussion, but in this comment my focus is on its implications for our understanding of the so-called "major transitions" in evolution, with special emphasis on the transition to human social organization. For the purpose of this comment, I accept the main tenets of OT, which I find mostly convincing.

Below, I first summarize what I see as the main differences in how OT and Maynard Smith and Szathmáry's (1995) "Major Evolutionary Transitions Theory" (METT) account for the evolution of complexity in biology. I then turn to two questions that are closer to my specific areas of expertise, which include the generalization of evolutionary theory (e.g., Stoelhorst 2005, 2008) and its application to human organization (e.g., Stoelhorst 2005; Stoelhorst and Richerson 2013). The first of these questions is what OT adds to the insights into the general nature of evolution offered by METT. The second is to what extent OT's additional insights shed light on the evolution of human behavior and organization.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_11

The main purpose of my comment is to resolve the paradox I faced when first discussing OT with its author: while I immediately found OT's ontology in the form of the "operator hierarchy" convincing, I could not accept Jagers' conclusion that human social organization does not qualify as a major transition. I argue that this paradox can be resolved once we recognize that OT shows the need for a much finer-grained understanding of major transitions than currently offered by METT.

11.2 How "Operator Theory" and "Major Evolutionary Transitions Theory" Differ

OT aims to identify the elemental building blocks of reality and to show how they relate to each other. It does so by imposing two criteria that elemental building blocks of reality should meet: functional and structural closure. These two criteria result in an elegant bottom-up ontology, called the operator hierarchy, which is visualized in Fig. 2.3 of this book. In Chaps. 8 and 10, Jagers contrasts his theory with METT, as originally developed by Maynard Smith and Szathmáry (1995) and recently updated by Szathmáry (2015). Confronting the two theories with each other leads Jagers to the conclusion that METT harbors ambiguities that OT can help resolve. Specifically, METT includes major transitions that OT excludes, such as, among others, the transition from RNA systems to DNA–RNA–protein systems, and the transition from primate societies to human societies. I come back to these two transitions below.

Upon closer analysis, the fact that the two theories generate different lists of the major transitions in evolution seems in large part the result of different conceptions of what a major transition is. While METT classifies transitions in functional terms only, OT insists on both functional *and* structural closure. These different views of major transitions, in turn, seem to emanate from the different purposes of the two theories. OT's main purpose is to unravel individuality, while METT casts its net rather more widely—presenting what Szathmáry (2015: 10104) refers to as "a 2D account" that seeks to unravel transitions in individuality *and* the evolution of informational systems. In fact, METT casts its net even more widely than this and may need to be understood as a 3D account. There is the additional link to "the notion of units of evolution that multiply, show inheritance, and have variability" (Szathmáry 2015: 10105). This third aspect of METT was central to the original work on major transitions: as Maynard Smith and Szathmáry (1995: 12, emphasis added) noted in their introduction, "[t]he idea of levels of organization, *and hence of levels of selection*, is central to this book."

Thus, while OT is single-mindedly focused on delivering a coherent ontology based on transitions in individuality only, METT attempts to unravel the nature of complexity by combining an interest in three different aspects of reality: individuality, the evolution of informational systems, and the units of selection in evolution. This difference in focus links in with another important difference between the theories, which is that OT is primarily axiomatic and deductive and METT primarily descriptive and inductive. Both theories take what we know about the nature of reality as their starting point and then try to unravel the way in which reality is organized. But in doing so, METT primarily reasons from what we know about the history of the evolutionary process, and from thereon tries to derive generalizations about the mechanisms that were operative in constructing what Dennett (1995) has referred to as the "cranes" that enabled ever more complex units of selection in evolution, such as DNA and human language. In contrast, OT posits the axioms of structural and functional closure as the necessary conditions for individuality and then interprets the organization of reality in terms of building blocks that meet these two conditions.

Given their different focus and approach, it is perhaps not surprising that the two theories end up with rather different notions of what constitutes a major transition. For Jagers, a major transition means a transition in individuality, which in turn requires both functional and structural closure, and there are fewer such transitions than the transitions recognized by METT. For Maynard Smith and Szathmáry, major transitions are a much broader, and, as a result, more amorphous phenomenon that they never seem to explicitly define. Instead, they merely point to a number of features that major transitions have in common. "The most important of these is that entities that were capable of independent replication before transition can replicate only as part of the larger whole after it" (Maynard Smith and Szathmáry 1995: 4)—a phenomenon that has since been referred to as "de-Darwinization" (Godfrey-Smith 2009; Szathmáry 2015). Two other features that are central are "the division of labor and a change in language" (Maynard Smith and Szathmáry 1995: 12).

11.3 What "Operator Theory" Adds to "Major Evolutionary Transitions Theory"

So we have two theories of major transitions that differ in their conception of what constitutes a transition, with OT taking the more stringent approach to the phenomenon by imposing the additional criterion of structural closure. This naturally leads to the question how the additional consideration of structural closure increases our understanding of major transitions. The answer to this question is that it allows OT to offer a much more convincing account of one of the three storylines in METT's "3D account" of major transitions, namely the storyline of the evolution of individuality.

There are three reasons for this assertion. The first two are the elegance of the operator hierarchy and the fact that it extends "downwards" to also include inorganic matter, thus providing a more complete picture than METT. The third is that OT does indeed seem to pinpoint a number of ambiguities in METT, as Jagers claims. Moreover, the ambiguities it pinpoints include (but are not limited to) all the ambiguities that Szathmáry (2015) highlights himself: (1) major transitions that were included in the original METT but removed in version 2.0; (2) major transitions that were not included in the original METT but introduced in version 2.0; and (3) the case of human eusociality, which Szathmáry (2015) discusses as a controversial case before coming to the conclusion that it *can* be understood as a major transition. All of these ambiguous cases fall nicely into place when seen through the lens of OT, which denies them status as major transitions in individuality.

In my view, then, OT offers a clear contribution to the particular storyline in METT that is Jagers' main focus, namely the storyline of individuality. But what about the other two storylines in METT's 3D account: the evolution of informational systems and the levels of selection in evolution? These two storylines are not OT's specific focus, yet I think that OT nevertheless offers some insights. Central among these is the need for a much finer-grained understanding of major transitions than the one thus far offered by METT.

Having referred to METT as a 2D account, Szathmáry (2015: 10105) states "I think this dual approach is a feature rather than a bug. It would be somewhat surprising if major achievements of evolution could be satisfactorily coerced into a Procrustean bed of either dimension." While this is an entirely reasonable position, especially for a theory that explicitly aims to tell the overall "grand" story of the evolution of biological complexity, it is also a position that is fully compatible with an interest in further unraveling one of these dimensions, *in casu* individuality, and then seeing how advances in our understanding of that particular dimension may affect METT's overall interpretation of major transitions.

Seen in this light, OT's improved understanding of the individuality dimension of major transitions offers at least two specific insights that lead to a finer-grained overall understanding of major transitions. The first insight is the distinction between the "upward," "inward," and "outward" dimensions of the evolution of biological complexity. This distinction strikes me as a particularly fruitful point of entry for a finer-grained understanding of major transitions because, as I argue below, it may help untangle the three features of major transitions identified by Maynard Smith and Szathmáry (1995): de-Darwinization, the division of labor, and a change in language.

The second insight is that explaining "individuality" and "levels of selection" are *not* the same problem. This insight is in line with my earlier comment that METT probably should be interpreted as a 3D, rather than a 2D, account of the evolution of biological complexity. On the 2D interpretation, METT is about the evolution of individuality and informational systems. On the 3D interpretation, METT is about the evolution of individuality, informational systems, and units of selection. As I argue next, separating out the units of selection problem from the evolution of individuality is central to resolving the paradox I flagged at the beginning of this comment: that while I find the operator hierarchy a very convincing ontology, I am also convinced that human societies constitute a major transition.

11.4 Reconciling Operator Theory with the Idea of Human Organization as a Major Transition

This paradox can be resolved once we see human societies as a major transition in the sense of the evolution of an additional level of selection, while recognizing that such a transition does *not* require the evolution of an additional layer of individuality.

In other words, we can simultaneously accept Jagers' conclusion that human societies are "merely" behavioral groups and do not represent a major transition in terms of individuality *and* METT's conclusion that human societies are a major transition, although "only" in terms of representing a new, collective-level, unit of selection.

This finer-grained understanding of major transitions in general, and the transition to human social organization in particular, is further reinforced if we interpret the various transitions recognized by METT along the inward, upward, and outward dimensions (see Fig. 2.5). Doing so helps untangle the various features of major transitions highlighted in METT. To recall, these features are de-Darwinization, the division of labor, and a change in language. The first of these is the feature "that entities that were capable of independent replication before transition can replicate only as part of the larger whole after it" (Maynard Smith and Szathmáry 1995: 4), or in other words de-Darwinization. The latter two features were originally introduced as follows (Maynard Smith and Szathmáry 1995: 12):

> "The idea of levels of organization, and hence levels of selection, is central to this book. Not all major transitions, however, can be analysed in this way. Perhaps the most important transition of all is between organisms in which both genetic material and enzymes were made of RNA (the RNA world) and modern organisms in which the genetic material is DNA and enzymes are proteins – a division of labor that requires that there be coding and translation. A second transition, which also involves a change in the language whereby information is transmitted and in the physical medium that carries that language, is the origin of human speech. We accept this as being the decisive step in the origin of specifically human society.
>
> We will meet these two characteristic – the division of labor and a change in language – repeatedly."

Two things in this quote are especially relevant. The first is the apparent conflation of levels of organization (i.e., individuality), levels of selection, and de-Darwinization. The second is the explicit recognition that the major transitions identified by METT are a rather mixed bag, and cannot all be analyzed in the same way. This second point is explicitly repeated in version 2.0, when Szathmáry (2015: 10104) states: "It has never been claimed that all transitions would possess all common features or that the possessed features would have uniform weights across all of the transitions."

But if METT's list of major transitions is indeed a somewhat mixed bag of phenomena, then the distinction between the upward, inward and outward dimensions of the evolution of individuality can perhaps help us sort out the similarities and differences among the various transitions that METT identifies. For instance, note that in terms of OT, the transition from an RNA to a DNA world takes place along the inward dimension, while the transition to human societies based on symbolic language takes place along the outward dimension—without either being a transition in terms of individuality, as defined in OT. Moreover, despite the fact that I am, in line with Maynard Smith and Szathmáry, convinced that human organization is a major transition based on a new (symbolic) language, at least in the sense of giving rise to an additional, collective, level of selection, I have always found their argument that this transition also involves a process of de-Darwinization unconvincing. But on a finer-grained analysis of the different types of transitions there is no longer a need to link transitions in the outward dimension to de-Darwinization.

More generally, based on my interpretation of OT, as outlined above, I suggest the following links between the various features of major transitions, as highlighted by METT, and the evolution of individuality, as highlighted by Jagers:

1. Transitions in terms of individuality lead to new operators: they require a new "language" that allows cooperation among lower level operators and they take place along the *upward* dimension, requiring both functional and structural closure.
2. De-Darwinization is the result of a process of increasing "division of labor" among the constituent elements of an operator along the *inward* dimension.
3. A process of increasing division of labor among the constituent elements of an operator along the *inward* dimension can lead to new emergent properties at the level of the operator (as in the case of the transition from an RNA to a DNA world).
4. New units of selection require a transition of individuality in the *upward* dimension, ***or*** a new language that allows for the emergence of cooperative behavioral groups along the *outward* dimension without closure and de-Darwinization (as in the case of the transition to human social organization).

11.5 Conclusion

I have argued that the main difference between Jagers' OT and Maynard Smith's and Szathmáry's METT is that the former offers both a more focused and more convincing account of transitions in individuality. Moreover, based on this account, OT suggests that the evolution of complexity needs to be understood as involving processes along three interrelated dimensions: upward, inward, and outward. The distinction among these three dimensions of the evolution of complexity suggests that the problems of individuality, de-Darwinization, and levels of selection are, *contra* METT, not one and the same. For instance, human social organization based on natural language is a major transition along the outward dimension, resulting in a new level of selection. But it does not involve de-Darwinization, nor does it constitute a transition in individuality. Overall, then, the OT does not only offer a convincing ontology but also suggests the possibility of a much finer-grained understanding of the major transitions in evolution.

References

Dennett DC (1995) Darwin's dangerous idea: evolution and the meanings of life. Penguin, London
Godfrey-Smith P (2009) Darwinian populations and natural selection. Oxford University Press, Oxford
Maynard Smith J, Szathmary E (1995) The major transitions in evolution. Oxford University Press, Oxford

Stoelhorst JW (2005) The naturalist view of universal Darwinism: an application to the evolutionary theory of the firm. In: Finch J, Orillard M (eds) Complexity and the economy. Edward Elgar, Cheltenham, pp 127–147

Stoelhorst JW (2008) The explanatory logic and ontological commitments of generalized Darwinism. J Econ Methodol 15(4):343–363

Stoelhorst JW, Richerson PJ (2013) A naturalistic theory of economic organization. J Econ Behav Organ 90(Suppl):S45–S56

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. Proc Natl Acad Sci 112(33):10104–10111

Chapter 12
Learning from Water: Two Complementary Definitions of the Concept of Life

Gerard A.J.M. Jagers op Akkerhuis

> *"There is such a deep entanglement between these two levels that both the collective and the individual organization of life are cause and consequence of each other. Nevertheless, it is important to underline that there is also a basic asymmetry between the individual (metabolic) network and the collective (ecological) one: both are self-maintaining and self-producing organizations, but only individual beings (organisms) are autonomous agents with a self-produced, active physical border, plus a high degree of functional integration among components, plus a machinery for hereditary reproduction*"
>
> (Ruiz-Mirazo et al. 2004).

Abstract The concept of life is central to biology and related life sciences, but there is no convergence on a definition. With the aim to resolve this problem analogies were studied between definitions of water and life. The concept of water refers to two phenomena: material particles (the H_2O molecules) and interacting water molecules (liquid water). Likewise, the concept of life can be viewed as referring to a property of special material particles (the organisms) and to the system of interacting organisms (the ecosystem). In a comparable way as chemical theory has solved the problem of defining the water molecule, one can apply the Operator Theory for solving the problem of defining the organism concept. The analogy with water subsequently offers inspiration for two ontologically distinct definitions of life: (1) a definition of life as a general indication for a property that all organisms have, and (2) a definition of life that refers to a system of interacting organisms. These two definitions refer to different ontological kinds and accordingly cannot be merged into a single definition. For this reason the concept of life can be viewed as involving two, complementary, definitions. It is discussed how findings based on the water-life analogy contribute to current discussions about the definition of life.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_12

12.1 Introduction

Since ancient times, defining the concept of life has remained an intellectual challenge (e.g. the works of Aristotle, Descartes and Kant). As reviews by for example Morales 1998, Popa 2003, Bedau and Cleland 2010 demonstrate, many viewpoints on the definition of life have been published that can be fitted into different schools of thought. In one school, for example, scientists suggest that a definition is either impossible or pointless (Emmeche 1997; van der Steen 1997; Hengeveld 2010; Machery 2012; Cleland 2012). In another school (e.g. Trifonov 2011) a pragmatic approach is followed in which the vocabulary of existing definitions is used for the identification of the most commonly used terms, which are subsequently merged into a single phrase, that presumably offers a comprehensive definition. In yet another school life is viewed as a property of organisms. In this school one finds for example a definition that is based on generalised concepts indicated as the "pillars of life" (Koshland 2002), while other definitions in this school focus on the first cell and its properties as inspiration for a definition of life (e.g. Gánti 1971; Russell et al. 2014). In addition a hierarchical approach to the concept of life has been proposed that is based on different kinds of organisms, while the organism concept is defined using the Operator Theory (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis 2010a). One can also find approaches that belong to a school that focuses on a diachronic viewpoint in which life is viewed as the results of evolutionary processes. The diachronic viewpoint focuses for example on chemical systems that are capable of Darwinian evolution (Deamer and Fleischaker 1994), or on a combination of autonomy and open ended evolution (Ruiz-Mirazo et al. 2004).

With the aim of identifying an approach which can increase consensus in the field, the ideas in this chapter are based on the assumption that water and life can be defined in an analogous way. The water analogy can also be found in the works of for example Benner et al. (2004) and Cleland (2012) and is used by these authors to indicate that in the old days people typically identified water by means of sensory observations, using for example colour, fluidity, the presence or absence of a meniscus, odour and sensory temperature (when poured on one's hands). In principle, any liquid that gave rise to sensory experiences similar to water, was named water. It was only after the development of the molecular theory that it became possible to define a water molecule and to define liquid water as a system that predominantly consists of interacting water molecules. Interestingly, after the development of chemical theory the concept of water suddenly referred to *two* subjects: (1) Water: a molecule with specific properties, and (2) Water: the liquid that emerges when many water molecules interact (the resulting fluid is normally observed or experienced as water). It has been indicated that non-trivial terms, such as water, cannot be defined to philosophical completeness (Schwartz 1977). It is suggested in this chapter that such philosophical obstacles can be handled by distinguishing and defining separately any homonymous meaning of water, e.g. water as a molecule and water as a liquid.

By dealing separately with homonyms one can distinguish between object-based and system-based definitions of water or life. In the case of water, the object-based viewpoint is represented by a water molecule and the system viewpoint is represented by water as a liquid of interacting water molecules. In the case of life, the object viewpoint is represented by the organisms (as a general indication of various kinds of “life molecules” of varying complexity), and the system viewpoints is represented by the ecosystem as a dynamic system of interacting organisms. An analogy like this does not imply that the processes of defining water and life will be identical in every detail. For example, to define a water molecule, one can use a generally accepted theory about molecular structure, whilst no theory for defining organismic structure has gained general acceptance yet. In the following paragraphs it is explored which pathways are available for closing this gap.

Wrapping up the above reasoning, this chapter focuses on obstacles, challenges and open questions concerning the definition of life. The goal is to identify criteria for a definition of life that are stringent and that potentially allow for a definition that has no exceptions. To work towards this goal, this chapter starts with an inventory of homonyms of the concept of life. Based on this inventory a limited number of concepts of life are selected that are defined in detail.

12.1.1 Homonymy

The current quest for a definition of life does not aim at including all the homonyms used in everyday communication. As a means to create an inventory of homonyms, and in addition to scientific publications (e.g. Sagan 1970, Popa 2003; Bedau 2007, Bedau and Cleland 2010) and sources on the internet, this book makes use of the results of interviews that were held on the 14th of November 2015 with visitors of the Smithsonian National Museum of Natural History. The visitors were asked for their first thought after being confronted with the concept of life. The visitors’ answers were grouped according to the following four major perspectives.

Perspective 1: *Life is something metaphysical, something that exists independently of matter*. This class brings together the viewpoints of people who, mainly from a religious perspective, view life as something metaphysical that can enter and leave the body. Answers in this class are: “A spark that illuminates the body”, “Life is given to you”, “Life is something mysterious” and “What created life?”. Metaphysical answers that were not linked to religion were: “Oh wow, a big word. It’s like so much, so grand” and “Knowledge is life”.

Perspective 2: *Life represents a period of experiences*. Quite a few visitors viewed life as a period, e.g. “The life of a plant”, “Live your life”, “To experience new things and learn from it”, “Making the best of yourself” and “You lead your life to share it”. A little girl with loving parents said: “Life is good”.

Perspective 3: *Life represents a concept that refers to properties of organisms*. The answers in this class all shared the idea that life has to do with organisms: “Organisms in general, living species”, “Things that are self-replicating or reproducing”, “Any living being, animals, creatures”, “Everything that is carbon based”, “A being with purpose, a sentient being” or “Entities that can selfreproduce through nucleic acids". A little boy took some time to answer the question, and then said enthusiastically: "Life is about wild things".

Perspective 4: *Life refers to a system with many organisms*. This view of life was reflected in some of the museum's texts, and in the following answers: "We hope to find life on Mars", "Life is about interactions between organisms", "Culture/ co-existing" or "Evolving things that form an ecosystem".

The interviews proved a rich source of inspiration. Among all the possible options, it was chosen to focus on material viewpoints. Due to this material focus some viewpoints were excluded initially, such as the viewpoint that life is the spark that illuminates the body. And a material focus also excludes diachronic interpretations, e.g. life as a period of activities and experiences. The link to experiences can be re-established by viewing living activity, being alive, or feeling alive, as the consequence of experiences that result from activities of organisms, for example when a cell responds to chemical gradients, or when a person reads a book. Accordingly, the following two viewpoints were selected as being the most relevant for this chapter: (1) The organismic view of life (referred to as O-life), and (2) The systemic view of life (referred to as S-life). In the following paragraphs, it is explored how definitions can be constructed for the concepts of O-life and S-life.

12.2 A Framework for Defining Water and Life

In accordance with the work of for example Oliver and Perry (2006) and Stoelhorst (2008) this book views a definition as a conceptual filter based on criteria. Definitions can propose filters for imaginary objects and their relationships (unicorns, devils, Donald Duck and his nephews), as well as for real world objects and their relationships (e.g. stamps, atoms that through their interactions forma molecule). Ideally, the criteria define a class of entities that includes all appropriate cases and excludes all inappropriate cases. A stringent definition would not be plagued by exceptions, and would for this reason be insensitive to counterexamples. The current efforts for creating stringent definitions make use of the ontology of the Operator Theory (Jagers op Akkerhuis and van Straalen 1999; Jagers op Akkerhuis GAJM 2001, 2008, 2009, 2010c, 2012a, c, 2014). As discussed in detail in Chap. 2 the Operator Hierarchy offers a ranking of special kinds of objects, called operators. Starting with fundamental particles, the ranking of all the kinds of operators includes the hadrons, the atoms, the molecules, the cells (bacteria, archaea), the endosymbiont cells (protozoa), the multicellulars (blue-green algae), the endosymbiont multicellulars (plants, fungi, algae) and the neural network organisms (called memon, such as a dolphin and a mouse). And if a thing consists of interacting operators, without itself being an operator, it is called an interaction system.

The link between the Operator Theory and the process of defining water and life is that the Operator Theory helps defining objects that can be used to define water and life. In this chapter it is assumed that the processes of defining water and life require similar decision steps (Fig. 12.1). Both for water and life the definition process must start with a theory about objects. When focusing on water first, one can

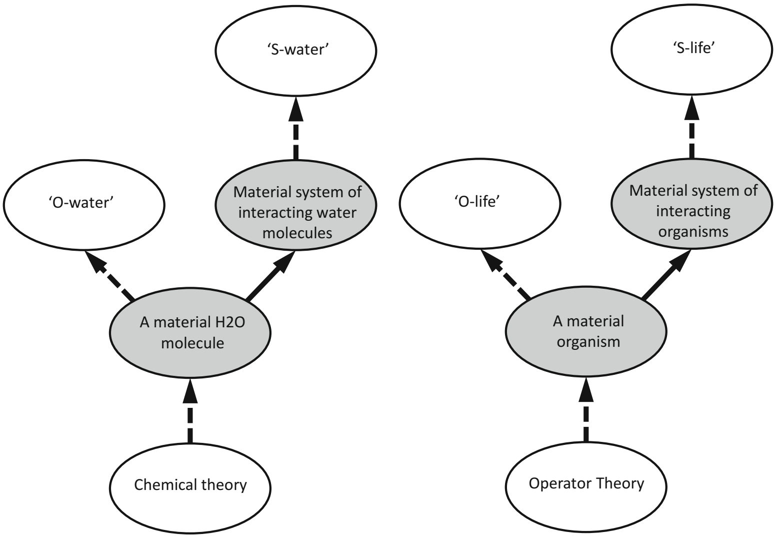

Fig. 12.1 Relationships used to analyse the processes of defining water and life. *Grey boxes* indicate material systems. *Dashed arrow*: conceptual relationship. *Solid arrows*: constructive relationships. O-water = the molecule oriented definition of water. *S-water* = the system oriented definition of water. *O-life* = the organism oriented definition of life. *S-life* = the system oriented definition of life

use chemical theory to define the objects, namely the water molecules. And water molecules can be used for an object oriented concept of water (O-water). Thereafter interacting water molecules can be used for defining a system oriented concept of water (S-water).

In a similar way one can look at life. Instead of using chemical theory, however, there are various reasons for using the Operator Theory as a basis for the following definition of the organism concept: "all operators of a kind that is at least as complex as the cell" (see Sects. 2.7.2, and 8.3). After defining the organism concept in this way, the definition can subsequently form the basis for an object oriented definition of life (O-life) and a system oriented definition of life (S-life). While Fig. 12.1 offers the basic pattern of the analogy, the details are examined in the following paragraphs.

12.3 An Object Oriented Definition of Water (O-Water)

To define a water molecule, one needs chemical theory. Chemical theory deals with the ways in which atoms and molecules can interact. An example is the process of covalent bonding, through which atoms form molecules. Every kind of atom has been linked to a symbolic representation. The symbolic representation of an oxygen atom is O, and that of hydrogen H. A single molecule of oxygen that has covalent bonds with two water atoms can accordingly be represented symbolically as H_2O. As the symbolic notation of H_2O refers to molecules of the kind water, people are used to say “H_2O is water”, even though is it more precise to say: “The symbol H_2O stands for the covalent bonding of one oxygen atom and two hydrogen atoms. The resulting molecule can in a general way be referred to as being of the kind water.” The link between a specific molecule and the term water can be viewed as an object oriented term, and as referring to O-water. The different concepts involved in

Table 12.1 Relationships between the process of defining water and life if one applies an object oriented perspective

Subject	Water molecule	O-Life
Theory involved	Chemical theory deals with questions about the classification and naming of different kinds of atoms and molecules, and with the question of how and why some atoms join to form molecules, and how and why molecules are produced in interactive processes	The Operator Theory studies the properties of all kinds of operators, and how lower level operators can lead to the next step in the operator hierarchy. The operator hierarchy offers an innovative perspective on which kinds of things are organisms
Material instantiation	The water-particle is the water molecule	The life-particle is the organism
Class membership	The class of water molecules includes several subclasses in the form of different kinds of heavy water molecules	The class of organisms includes several subclasses representing all the kinds of operators which are at least as complex as the cell. Every kind of operator is defined by its typical, level dependent combination of structural and functional closure. These subclasses are: the cell, the endosymbiont cell, the multicellular, the endosymbiont multicellular, and the neural network organism (named a memon)
Criteria (class)	The class includes all the water molecules (the molecules that consist of one oxygen atom being connected through covalent bonds with two water atoms)	The class includes all the operators that are at least as complex as the cell. If on a planet only a single organism is present, the criterion of the presence of organismic life has been fulfilled
Criteria (single object)	When speaking about a single molecule, water refers to a specific molecular configuration. After having lost this configuration the molecule no longer represents water	When speaking about a single organism, life refers in a general way to the presence of the typical closures. When losing one or two of its typical closures the remaining system no longer represents life
How to refer to the object in question?	The H_2O molecule is addressed as a water molecule or simply as water (which refers to O-water)	An organism is also addressed as a living being (a “life particle”) or as a “life form”
Limit cases		Frozen organisms and dried seeds still possess their typical closures. Accordingly, and technically speaking, activity is not a demand for objects in the class of the organisms. Objects that are not an operator are excluded from the definition

defining water as a kind of molecule are summarised in the second column of Table 12.1.

12.4 An Object Oriented Definition of Life (O-Life)

Until recently, science did not have a theoretical framework for defining the concept of the organism. As was indicated above, the Operator Theory has offered a means to improve on this situation. With the help of the ontology of the Operator Theory the organism concept has been defined as follows: "*all operators of a kind that is at least as complex as the cell are organisms*" (Jagers op Akkerhuis 2010a, 2012b, see also Sects. 2.7.2, 8.2 and 8.3). The Operator Theory thus scaffolds a definition of the organism concept just as chemical theory scaffolds the definition of water molecules. While chemistry uses covalent bonding for explaining the integration of an oxygen atom with two water atoms, the Operator Theory uses dual closure for explaining the emergence of cells and the ways cells join and form different kinds of organisms. In Chap. 2 the concept of dual closure is discussed in detail (see also for example Heylighen 1990; Chandler & van de Vijver 2000; Jagers op Akkerhuis 2010c).

The operator-based definition of the organism concept now allows for an object oriented definition of life (O-life). This definition starts with the realisation that every organism is an operator. Every operator has its typical, level-dependent structural closure and its typical, level-dependent functional closure, which together are indicated as dual closure (see Chap. 2). As a consequence, the presence of the dual closure in every operator that classifies as an organism, but not in other operators, can be viewed as a general criterion that allows for the following object oriented definition of life (O-life): "*life is a general term for the presence of dual closure in every operator that is an organism*". This definition of O-life refers to specific properties a system must have in order to have the complex quality of life. According to this definition, a system that is not an organism cannot possess the quality of life. The O-life quality is lost as soon as one of the aspects of dual closure is lost. After such loss the system classifies no longer as an operator, nor as an organism. Technically speaking, an organism can be alive, be living or be dying, but cannot be dead. The reason is that a corpse, or cadaver, no longer classifies as an organism, and for this reason does not possess the agency to "be" something. This means that a corpse can be neither alive nor dead. It is relevant in this context to remark that the presence of dual closure is based on topological criteria, and that for this reason the presence of closure is independent of whether or not an organism is active. Accordingly, an organism does not have to be "living" or to "be alive" to have the quality of O-life. Frozen and/or desiccated organisms may still possess their closure topologies, and by reviving them (Broca 1860; Becquerel 1950) one can prove they still possessed the quality of O-life while they were inactive. The inactivity of revivable organisms has also been referred to as viable lifelessness (Keilin 1959).

12.5 An Interaction System Based Definition of Water (S-Water)

Above the object oriented concept of water was defined by referring to the water molecule H_2O. With this molecule as a basis, one may define a system of interacting molecules as S-water. However, this way of defining S-water requires some additional thoughts. The reason is that if many water molecules are placed together in a container, and allowed to interact, some of the molecules will undergo changes. For example, some molecules in the container may dissociate, and cause the production of H^+ and OH^- ions. And the H^+ may form a jointure with H_2O to form $H3O^+$. Moreover, water molecules in the container will orient their electrically charged ends (O is negative, and H is positive) in such a way that the orientation of all water molecules in the liquid deviates from a random distribution. In addition, the amount of dissociated molecules and of molecular orientation may change in dependence of temperature and pressure. Meanwhile, water can turn into vapour, or become ice. Such transitions between phases have been described by means of phase diagrams. The description of liquid water thus can be linked to a specific region in the phase diagram. All the properties, such as the amount of dissociated molecules, the pH, the aligning of molecules, and liquidity in a specific area of the phase diagram, are emergent properties of interacting water molecules. Such emergent properties are natural aspects of S-water. Based on this insight, S-water can be defined as: "*the concept that refers to an interaction system of water molecules in a liquid phase, including all associated emergent properties*". As long as S-water refers to a liquid that is selectively based on interacting H_2O molecules (including emergent properties), one can speak of pure water. When other non-water-derived atoms or molecules are dissolved in the water, one can speak for example of a water-based mixture/solution/suspension. As long as water molecules are the dominant component, and the solution has the look and feel of water, most people will refer to a mixture/solution/suspension as water, or use other names, such as polluted water, seawater, soda water, and whiskey.

12.6 An Interaction System Based Definition of Life (S-Life)

With the help of the Operator Theory one can define and rank all the kinds of operators, and classify a subset of operators as organisms. Such insight offers a foundation for defining a system of interacting organisms in analogy with S-water. In the preceding chapters S-water was defined as: "*the concept that refers to an interaction system of water molecules in a liquid phase, with all associated emergent properties*". By analogy, S-life can now be defined as "*the concept that refers to an interaction system of organism, while in a dynamic state, including all the emergent properties that follow from the interactions*". In contrast to water, where the system itself is called water, the concept of S-life refers to a kind of interaction system that

Table 12.2 Relationships between the process of defining water and life if one applies a system oriented perspective

Interaction system viewpoint	Liquid water	S-Life
Material instantiation	S-water is a concept that refers in an abstract way to the interaction system that is produced by interacting water molecules. Such a system is called water	S-life is a concept that refers to the interaction system that is produced by interacting organisms. Such a system is exemplified by any ecosystem inhabited by two or more interacting organisms
Class membership	The class of instances of pure water refers to all interaction systems that consist of interacting water molecules in the liquid phase and all the emergent properties that follow from the interactions in the system	The class of instances of S-life includes all interaction systems in which organisms interact with each other and all the emergent properties that follow from the interactions in the system
Criteria	Pure water takes the form of a liquid (as physically determined by the phase diagram) and naturally represents a dynamic balance between H_2O molecules and a small percentage of dissociated OH^- and H^+ and some other naturally formed complexes	Technically speaking, the criterion of interactions between organisms is sufficient for S-life. This implies that the presence of a single organism on a planet does not represent S-life. S-life minimally requires two organisms and some kind of interaction
Related systems	When speaking about impure water or a mixture, various kinds of chemicals can be dissolved in the mixture at various concentrations	If the criterion of interactions between organisms is met, one can discuss the additional occurrence of reproduction. And when reproduction takes place, the pattern of Darwinian evolution may be realised

is based on two or more interacting organisms. Accordingly, S-life refers to a special kind of ecosystem. Based on the Operator Theory, there is a subtle difference between an ecosystem and the system that is referred to by S-life. According to the Operator Theory, a chemosystem chances to an ecosystem, the moment that the first organism is formed in the system, or immigrates into it. The concept of S-life, however, demands that there are two or more interacting organisms in the ecosystem. Accordingly, the sentence “Is there S-life on a planet” can be viewed as an abstract reference to the presence of an ecosystem with two or more organisms. If in a local region of the ecosystem the organisms are frozen, there will be no interactions between organisms in this region, and the system in this region will not classify as S-life. At the same time, some frozen organisms in this region may still meet the criteria for O-life (as long as the frozen organisms can be thawed and revived). Table 12.2 offers a comparison of the concepts used for defining liquid water and for defining the systems view of life.

12.7 Discussion

In this section, the conceptual results of this chapter, including the definition of the organisms, and the distinction between O-life and S-life, are related to ongoing debate about definitions of life. For this purpose, the debate is split up according to the following topics: (1) The process of defining life, (2) The question of whether life can be generalised beyond Earth life, (3) The use of "levels" of life and (4) The selection of criteria for life.

12.8 Contributions to the Process of Defining Life

To recognise life one needs a definition of life, while as a basis for a definition of life one needs to identify "appropriate" examples of entities that represent life. In order to solve this challenging catch 22 Bedau (1998), Sterelny and Griffith (1999), Cleland & Chyba (2002, 2007) and others, have suggested that a theory of life must precede a definition of life.

By analogy with water, where chemistry and molecular theory have offered a foundation for a definition of the water molecule (H_2O), a "life theory" is needed as a foundation for defining the organism. As a theory for organisms, this book has made use of the Operator Theory, which theory defines all the kinds of operators, and selects a subset of these as organisms. Using the Operator Theory as a foundation, the concept of O-life was defined as the general term for the presence of the typical closures found in organisms. As the next step organisms and their interactions were used for defining the concept of S-life.

The above insights can be applied when discussing the relationship between the concept of O-life and the concept of a living being. While every organism necessarily complies with the criteria of O-life, it is not possible to view an organism as a material instantiation of O-life. The reason is that in the context of the Operator Theory, the concept of O-life is viewed as a general term for the presence of dual closure in organisms. O-life thus refers to the possession of a complex quality. While the quality of O-life can be possessed by an organism, in the sense that it "has" its dual closure, this does not mean that an organism can be viewed as a material instantiation of such quality, because an organism does not represent its closures, but represents more than that. The realisation that the concept of O-life may have no material instantiations suggests strongly that a definition of O-life cannot be viewed as referring to a category of nature which exists independently of human thought (such as a gold atom), which categories are called natural kinds. The deduction that O-life is not a natural kind accords with the work of Fox Keller (2002) and Cleland and Chyba (2007). This conclusion leaves unabated that every single organism represents a material instantiation of the organism concept, while the organism concept refers to a broad range of natural kinds represented by all the kinds of organisms that are ranked by the Operator Hierarchy.

The situation is different for S-life. S-life is defined as a concept that refers to an interaction system based on organisms, including all the emergent properties that follow from such interactions. Because of this definition, any part of the universe in which operators of the kind organism interact with each other (and with their environment) can be viewed as a material instantiation of the S-life class of systems. And because a material interaction system that instantiates the class of S-life can exist independently of its conceptual definition (e.g. the Earthen ecosystem existed before humans entered the scene), it can be viewed as a natural kind.

The ideas expressed so far lead to the conclusion that two different definitions of life can be constructed with different meanings: O-life and S-life. Such results offer a different view on the subject than for example Emmeche 1997, van der Steen 1997, Hengeveld 2010 and Cleland 2012, suggesting that it is not possible or not desirable, to define life. Meanwhile, the current results may also help solving ambiguity about existing definitions of life by taking into account that O-life and S-life represent fundamentally different ontological kinds, which cannot in a consistent way be combined into a single definition. The results also suggest that some definitions which aim at combining both the level of the organism and of the system actually focus on the latter level, by emphasising for example a network made out of self-reproducing agents (Ruiz-Mirazo et al. 2004). According to the current perspective, such a network would represent an instantiation of S-life. The current pair of definitions also supports the argumentation of Jagers op Akkerhuis (2012c) that when defining life, it is insufficient to base a definition on the most frequently used words that are selected from the vocabulary of existing definitions (Trifonov 2011).

12.8.1 Contributions to Whether or Not the Concept of Life Can be Generalised Beyond the Earthen Situation

At present, the scientific knowledge of life is limited to experiences with earthen life. Because of this limitation, it has been questioned whether or not the single example of earthen life, and the stuff that earthen life is made of, can form a suitable foundation for a general definition of life? (Benner et al. 2004, Cleland and Chyba 2007). It is suggested here that this question can be answered, at least in part, by viewing earthen organisms and S-life as local representations (“instantiations”) of more general classes, and by including observations from other celestial bodies than the earth.

Both O-life and S-life make use of the organism concept. For this reason the question about generality of the definition of life depends on the generality of the definition of the organism. In relation to this subject it is relevant that every organism is an operator and has dual closure (e.g. Jagers op Akkerhuis 2012c). As long as dual closure is present, it does not matter whether a bacterium is red or blue, has DNA, RNA, XNA or any other kind of coding molecule in its autocatalytic set, is carbon based or based on other chemicals etc. The two typical closures of earthen organisms can thus be viewed as a general feature that potentially is not limited to earthen life.

How can it be investigated whether or not the validity of the definition of O-life that is based on the Operator Theory is general, in the sense that it applies also to life outside the Earth? This question can be answered at least in part by referring to cosmological observations of lower level operators than organisms.

Measurements of absorption spectra in the light of stars everywhere around us in the visible universe have proven that low level operators such as atoms and molecules exist throughout the universe. And measurements on the moon also have confirmed the presence of many kinds of atoms and molecules. As molecules consist of atoms, and atoms consist of hadrons and fundamental particles, e.g. quarks and electrons, the existence of atoms implies the existence of quarks and hadrons. Apparently, earthen conditions have not been critical for the formation of low level operators, such as quarks, atoms and molecules. As earthen conditions have not been critical for the forming of low level operators, it can be hypothesised that earthen conditions will neither be critical for the formation of the higher level operators called organisms. The Operator Theory thus connects observations on planet Earth and observations outside the Earth. As the definitions of O-life and S-life in this chapter were based on the Operator Theory, such definitions inherit the generality of the Operator Theory. Thus while closure-based definitions fit in with all examples of earthen life, earthen examples of organisms can be viewed as local instantiations of closure kinds. Accordingly, it is quite safe to assume that the validity of definitions based on the Operator Theory extends beyond earthen life.

Even though the definition of O-life is general, it still allows for sharp distinctions of borderline cases, such as viruses, prions, computer intelligence (e.g. Ray 1991; Sims 1994), as well as for the distinction of life and living, and of the start and end of a life (Fox Keller 2002). In Jagers op Akkerhuis (2010a, b; 2012c) many examples have been offered of how the definition of O-life allows one to deal with difficult cases. Just as an example: a complex virus with capsid and membrane still lacks the closures that according to the Operator Theory are required for a cell. Without these closures, such a virus is viewed as an interaction system of molecules. And the simplest form of a virus that exists of nothing more than a strand of DNA/RNA, and is called a viroid, would classify as a molecule. For this reason, a virus is not viewed as a borderline case, because it can be classified either as an interaction system, or as a molecular operator, but never as an organism.

12.8.2 Contributions to the Thinking About Levels of Life

The Operator Theory offers a natural context for the distinction of levels of life, based on the following kinds of organisms: the cell, the cell with endosymbionts, the multicellular organism, the neural network organisms (memons), and—in the future—various kinds of technical memons. As discussed in Jagers op Akkerhuis (2010b), this also implies that a general definition of life, which covers all the kinds of organisms, cannot be derived from just one kind of organism, regardless of whether this organism is a first cell, a protocell or a minimal cell (Luigi Luisi et al. 2006; Gánti 1971; Norris and Raine 1998).

The above ideas about levels can be linked to ideas of Gánti (1971) about primary, secondary and tertiary life in the following way. Primary life applies to the operator kind called a cell. Secondary life applies to the multicellular organism and its internal organisation. And tertiary life applies to groups of organisms. Meanwhile the Operator Theory classifies groups as interaction systems, instead of as operators/organisms or as life. By analogy, the first, second and third order autopoiesis of Maturana (1980) relate to the organism, the multicellular organism and the ecosystem, respectively.

Now that the current book has shown that it is practical to distinguish between O-life and S-life, this viewpoint corresponds with the distinction that Ruiz-Mirazo et al. (2004) make between an individual-based metabolic view of life and a collective-based view of life. Finally, some authors have suggested that proto-cells represent the first primitive life-forms. However, the Operator Theory does not include the level of the proto-cells, because depending on its construction, a proto-cell will either classify as a cell, or as an interaction system.

12.8.3 Contributions to Criteria for Defining Life

A practical contribution of the current results to the endeavour of defining life is that many properties which have been suggested as representing hallmarks of life, can be re-conceptualised as being the products of the activities of organisms, and hence as O-life. In line with the work of Boden (2000) on autopoiesis the closures represented by set-wise autocatalysis and the membrane of a cell form a basis for discussing other derived properties, such as metabolism, genetics (as part of the autocatalytic set), information (referring to the "meaning" of autocatalytic molecules for the entire set and for the relationships of the organism with the outside world), growth, response to stimuli, reproduction, and a container. All such derived properties have their foundation at a lower conceptual level of explanation, namely the level of dual closure. And when a dual closure in organisms is used as the criterion for O-life, the resulting definition does no longer demand activity, growth or reproduction. Activity, growth and reproduction are potential consequences of the dynamics of organisms. Meanwhile, an organism remains an organism even when it is not active, growing or reproducing. The latter viewpoint solves for example problems with mules, as well as problems with frozen bacteria and other examples of viable lifelessness.

With respect to S-life, the minimum requirement is that a system has at least two organisms that interact. There is space for elaboration and specification now, because the interactions can take different forms, e.g. predation, social interaction and competition for food. And if conditions are favourable the interactions may lead to growth and reproduction. In turn, reproduction may lead to the pattern of Darwinian evolution. These steps show that reproduction and Darwinian evolution are not required, but *may occur* in an S-life system. Based on the criterion of Darwinian evolution, it has been suggested that a single rabbit does not represent life, because it cannot reproduce, and cannot support Darwinian evolution (Benner et al. 2004). Indeed, by lack of interactions with other organisms, a single rabbit would not meet the criteria for S-life. However, the lonely rabbit would still meet all criteria for O-life.

12.9 Summary and Conclusions

In this chapter it was examined how the definition of water could offer inspiration for defining life. As part of the results, it was shown that chemical theory offers a foundation for defining water molecules much in the same way as the Operator Theory offers a foundation for defining organisms. After defining organisms, these can be used as the foundation for defining O-life and, by analogy with how molecules can be used for defining liquid water, for defining S-life. The results indicate that O-life holds a more central position in science than S-life. The reason is that O-life is connected through the organism concept with a broad range of other concepts, such as living, being alive, viable lifelessness, life as a period, life as an experience, and dying and death. In contrast, the systems definition of life (S-life) applies selectively to the active state of an interaction system based on organisms. While the concept of O-life therefore seems to be the most fundamental for scientific communication, the concept of S-life has a major use in very general accounts of life, such as "In between of mass extinctions, life can be relatively stable".

12.10 Conclusions

- It was explored whether or not organisms and life could be defined by analogy with water molecules and water.
- The organism concept was defined as referring to any operator of a kind that is at least as complex as the cell.
- It was proposed to distinguish between an organism oriented definition of life (O-life) and a system oriented definition of life (S-life).
- O-life was defined as a general term for the presence of the typical closures in organisms (this definition of life refers in a stringent way to qualities only organisms have). An inactive organism still possesses its typical closures, and still has life, even though it is not living.
- S-life was defined as referring to an interaction system that is based on organisms while demanding that the system be in a dynamic state.
- The results of this chapter contribute to the quest for a definition of life by drawing attention to the fundamental ontological difference between O-life and S-life and to the ontological reasons why both definitions cannot be viewed as different aspects of the same concept.

References

Becquerel P (1950) La suspension de la vie des spores des bactéries et des moisissures desséchées dans le vide, vers le zéro absolu. Ses conséquences pour la dissémination et la conservation de la vie dans l'univers. Les Comptes rendus de l"Académie des sciences, Paris, 231: p 1274, pp 1392–1394

Bedau MA (2007) What is life. In: Sarkar S, Plutynski A (eds) A companion to the philosophy of biology. Blackwell Publishing, New York. pp 455–603

Bedau MA (1998) Four puzzles about life, vol 4, Artificial life. MIT Press, Cambridge, MA

Bedau MA, Cleland CE (2010) The nature of life. In: Bedau MA, Clevand CE (eds) Classical and contemporary perspectives from philosophy and science. Cambridge University Press, Cambridge, UK

Benner SA, Ricardo A, Carrigan MA (2004) Is there a common chemical model for life in the universe? Current opinion in chemical biology 8:672–689

Boden MA (2000) Autopoiesis and life. Cognit Sci Quarterly 1:117–145

Broca MP (1860–1861) Rapport sur la question soumise à la Société de Biologie au sujet de la reviviscence des animaux desséchés. Mém Soc Biol, 3me Série, II, 1860: 1–139

Chandler JLR, van de Vijver G (Eds) (2000) Closure: emergent organizations and their dynamics. Ann N Y Acad Sci 901

Cleland CE (2012) Life without definitions. Synthese 185:125–144

Cleland CE, Chyba CF (2002) Defining "life". Origins of life and evolution of the biosphere 32:387–393

Cleland CE, Chyba CF (2007) Does "life" have a definition? In: Sullivan III, Woodruff T, Baross JA (eds) Planets and life: the emerging science of astrobiology. Cambridge University Press, Cambridge

Deamer DW, Fleischaker GR (eds) (1994) Origins of life: the central concepts. Jones & Bartlett, Boston

Emmeche C (1997) Autopoietic systems, replicators, and the search for a meaningful biological definition of life. Ultimate Reality and Meaning 20:244–264

Fox Keller E (2002) Making sense of life: explaining biological development with models, metaphors and machines. Harvard University Press, Cambridge, MA

Gánti T (1971) The principle of life (in Hungarian). Gondolat, Budapest

Hengeveld R (2010) Definitions of life are not only unnecessary, but they can do harm to understanding. Foundations of Science 16:323–325

Heylighen F (1990) Relational closure: a mathematical concept for distinction-making and complexity analysis. In: Trappl R (ed) Cybernetics and systems "90. World Science, Singapore, pp 335–342

Jagers op Akkerhuis GAJM (2001) Extrapolating a hierarchy of building block systems towards future neural network organisms. Acta Biotheoretica 49: 171–189

Jagers op Akkerhuis GAJM (2008) Analyzing hierarchy in the organization of biological and physical systems. Biol Rev 83: 1–12

Jagers op Akkerhuis GAJM (2009) The Operator Hierarchy: Evolution Beyond Genes. Abstract of a poster presentation at ECAL 2009, Budapest

Jagers op Akkerhuis GAJM (2010a) Towards a hierarchical definition of life, the organism, and death. Foundations of Science 15: 245–262

Jagers op Akkerhuis GAJM (2010b) Explaining the origin of life is not enough for a definition of life. Foundations of Science 16: 327–329

Jagers op Akkerhuis GAJM (2010c) The Operator Hierarchy. A chain of closures linking matter, life and artificial intelligence. Ph.D. thesis Radboud University Nijmegen.

Jagers op Akkerhuis GAJM (2012a) Contributions of the operator hierarchy to the field of biologically driven mathematics and computation. In: Integral biomathics: tracing the road to reality

Jagers op Akkerhuis GAJM (2012b) The pursuit of complexity. The utility of biodiversity from an evolutionary perspective. KNNV. pp 120

Jagers op Akkerhuis GAJM (2012c) The role of logic and insight in the search for a definition of life. J Biomol Struct Dyn 29(4):619–620

Jagers op Akkerhuis GAJM (2014) General laws and centripetal science. Eur Rev 22:113–144

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego–bricks of nature: evolutionary transitions from fermions to neural networks. World futures. J Gen Evol 53: 329–345

Keilin D (1959) The Leeuwenhoek lecture: the problem of anabiosis or latent life: history and current concept. Proc Roy Soc Lond B Biol Sci 150:149–191

Koshland DE Jr (2002) The seven pillars of life. Science 295:2215–2216

Luigi Luisi P, Ferri F, Stano P (2006) Approaches to semi-synthetic minimal cells: a review. Naturwissenschaften 93:1–13

Machery E (2012) Why I stopped worrying about the definition of life… why you should as well. Synthese 185:145–164

Maturana HR, Varela FJ (1980) Autopoiesis and Cognition. The realization of the living. Dordrecht: D. Reidel, (also in Boston Studies in the Philosophy of Science, 42)

Morales J (1998) The definition of life. Psychozoan 1 (a strictly electronic journal): 1–39

Norris V, Raine DJ (1998) A fission-fusion origin for life. Orig Life Evol Biosph 28:523–37

Oliver JD, Perry RS (2006) Definitely life but not definitely. Origin Life Evol Biosphere 36:515–521

Popa R (2003) Between necessity and probability. Searching for the definition and the origin of life, Advances in astrobiology and biogeophysics. Springer, New York

Ray TS (1991) Evolution and optimization of digital organisms. In: Billingsley KR, Derohanes E, Brown H, III (eds) Scientific excellence in supercomputing: The IBM 1990 Contest prize papers, Athens, GA, 30602: The Baldwin Press, The University of Georgia. pp 489–531

Ruiz-Mirazo K, Pereto J, Moreno A (2004) A universal definition of life: autonomy and open-ended evolution. Origin Life Evol Biosphere 34:323–345

Russell MJ, Barge LM, Bhartia R, Bocanegra D, Branscomb E, Bracher PJ, Kidd R, McGlynn S, Meier DH, Nitschke W, Shibuya T, Vance S, White L, Kanik I (2014) The drive to life on wet and icy worlds. Astrobiol 14:308–343

Sagan C (1970) Life. Encyclopedia Brittannica. pp 1083–1083A. Chicago: Encyclopedia Brittannica Inc.

Schwartz SP (1977) Introduction. In: Schwartz SP (ed) Naming, necessity, and natural kinds. Cornell University Press, Ithaca, NY

Sims K (1994) Evolving 3D morphology and behavior by competition. In: Brooks RA, Maes P (eds) Artificial life IV: proceedings. MIT Press, Cambridge, MA, pp 28–39

Sterelny K, Griffith P (1999) Sex and death: an introduction to philosophy of biology. University of Chicago Press, Chicago

Stoelhorst JW (2008) The explanatory logic and ontological commitments of generalized Darwinism. J Econ Methodol 15:343–363

Trifonov EN (2011) Vocabulary of definitions of life suggests a definition. J Biomol Struct Dyn 29:259–266

van der Steen WJ (1997) Limitations of general concepts: a comment on Emmeche's definition of "life". Ultimate Real Mean 20:317–320

Chapter 13
Adding (Thermo)dynamic Aspects to Definitions of Life

Michael Russell

Abstract Jagers op Akkerhuis suggests two complementary definitions of life: O-life and S-life. O-life represents the organismic view of life, focusing on a general property of organisms. S-life refers to the systemic view of life, and is represented by a system of interacting organisms. As a contribution to defining life by means of organisms and interacting organisms, it is relevant to focus on the fundamental chemical processes that allow for the existence of organisms. From this point of view, this contribution will focus on the chemistry of chemo-autotrophic cells, and the thermodynamic disequilibrium that cells need for their functioning.

13.1 Introduction

Chapter 12 uses the distinction between an organism and an ecosystem as a basis for defining two complementary concepts of life. As both concepts make use of the organism, this concept is defined first. To define the organism concept the so-called Operator Hierarchy was used as a foundation. Only those kinds of operators in the Operator Hierarchy that reside at the level of the cell or at a higher level are accepted as organisms.

After defining the organism concept in this way, the first definition of life was linked to the fact that every organism has dual closure (dual closure being defined in Chap. 2). The assumption is that as long as an organism has its dual closure it accords with the criteria for life. This way of defining life is referred to in the chapter as the organismic definition, hence O-life.

In addition to the organismic definition Chap. 12 also suggests that the concept of life can be related to a system of interacting organisms. Now life is defined as a system in which two or more organisms interact with each other and with the environment, and all emergent aspects that follow from such dynamics. This way of defining life is referred to as systemic life, hence S-life.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_13

The suggestions for distinguishing O-life and S-life are important considerations for the life sciences in general which, unlike the "hard" sciences, as yet have no underlying theoretical base to their disciplines.

With the above definitions Jagers op Akkerhuis links to discussions about life in the work of, e.g., Cleland, Bedau, and Moreno. What is added is the use of dual closure and of the Operator Hierarchy as a foundation. Due to such foundations challenges of defining life by analogy with defining water seem to have been solved.

13.2 Thermodynamic View of Organisms and Life

What, in my opinion, could be added to the above viewpoint is that, in terms of the second Law of Thermodynamics, both an organism, the agent that complies with O-life, and an ecosystem, which complies with S-life, may be considered, like other active dynamic phenomena in the Universe, as engines of entropy generation, i.e., both work within Boltzmann's *Statistical* Entropy Law (Branscomb and Russell 2013 and see Schrödinger 1967). Indeed, the second law is not an obstruction to the operations of organisms or ecosystems as so often assumed, but its ultimate driver. In these terms we may expand on the *Operator Theory* just outlined, to consider *Operational Definitions of Life* and see if the definitions of both O-life and S-life may be enriched with the help of thermodynamic considerations. The *operational definitions* suggested here are that:

1. Overall, all autotrophic organisms hydrogenate carbon dioxide (as the first cells will have done).
2. Cells are compartmentalized and homeostatic (which properties correlate with the structural and functional closures of organisms that are mentioned in Chap. 12).
4. Organisms are entropy transducers working far-from-equilibrium in a Brownian environment (Branscomb and Russell 2013).
5. Systems that consist of organisms are exploratory through Darwinian evolution and are recursive in their flows of free energy and minerals.
6. The functioning of organisms in ecosystems is involved in multiple feedbacks to our wet and rocky planet which lead to a 2 orders of magnitude increase in the number of mineral types over the abiotic Earth's first inventory (Allen 2010; Russell and Kanik 2010; Hazen et al. 2008; Russell et al. 2013).

Operational definitions per se—as required for theory generation—are not generally considered in the life sciences, which stems in part from the historical fact that bacteria (and eventually the archaea) were discovered, or at least given their rightful position at, and near, the base of the evolutionary tree, *after* Darwin and others had established the first tree—a tree to either fascinate or appal their viewers. "The Descent of Man" begins with an outline of the homologies of "man" with the "lower animals." Man, as part herbivore and part carnivore, considers food as ultimate fuel and this bias became embedded into the subconscious of scientists. This almost biblical assumption led to the mistaken view that life, and its birthing, is and was, heterotrophic. This in turn led to the unquestioning acceptance of the

Oparin-Haldane organic soup hypothesis for the origin of life, an idea seemingly supported by the spark-discharge experiments of Miller and Urey. Yet everything we eat, burn, and bag is derived from carbon dioxide. And we now know that the evolutionary tree is planted in autotrophy, as is today's food web. We, and the other animals, are merely heterotrophic eddies in the generation of organic molecules and other waste products from CO_2 and H_2, with additions approximated by the Redfield ratio along with an inventory of trace metals (Hazen et al. 2008; Maret 2016).

Two major mechanisms, one geochemical the other photochemical, are responsible for providing the hydrogen fuel to the base of the food web—oxygenic photosynthesis being the most productive. In the earliest autotrophic organisms the hydrogen fuel was, and is still, released from water in hydrothermal processes that oxidize iron in the Earth's crust from the ferrous to the ferric state. In this case, the oxygen is left behind in the Earth's crust in magnetite (Fe_3O_4):

$$H_2O + 3(FeO)_{\text{silicate}} \rightarrow H_2 + Fe_3O_4$$

But hydrogen alone cannot reduce the CO_2. It needs to be split into electrons and protons first. As the electrons are more mobile than the protons, they separate and the electrons are drawn vectorially to oxidized molecules such as nitrate and ferric iron on the outside of the (emergent) cell. At the same time, protons on the outside are driven inward across the membrane.

In the oxygenic photosynthetic mechanism the reduction is driven on site. Hydrogen is released from water by the action of photons on the manganese-bearing oxygen evolving complex. The oxygen waste (as well as water) is thence freed as a gas to the atmosphere (as O_2):

$$2nCO_2 + 4nH_2O + \text{photons} \rightarrow 2\{CH_2O\}_{n(\sim\text{life})} + 2nH_2O + 2nO_2 -$$

So organisms do not just carry out a special kind of geochemistry; they are really different—they work by harnessing (vectorial) gradients. Indeed, were geochemical reduction of carbon dioxide to methane facile there would be no call for life—hence Operational Definition 1.

These chemo- and photo-synthetic reactions along with the heterotrophic biochemical reactions relying on autotrophy require enzymes that couple endergonic (thermodynamically-uphill) reactions to necessarily larger exothermic (thermodynamically-downhill) reactions. Enzymes (literally nano-engines and not, or not merely, catalysts) have continued to self-optimize over time, fuelled by two or more of vectorial electron, proton, or photon gradients. How these enzymes work is counterintuitive, operating on a ratchet or escapement principle in which the free energy is used to trap an endergonic reaction after it has been driven "uphill" by Brownian fluctuations in a process reminiscent of deficit spending (Danyal et al. 2011; Hoffmann 2012), an echo of the suggestion that during the inflationary period, the Universe borrowed heavily from gravitational energy, a debt that will not have to be paid until the end of the Universe (Hawking and Hawking 1994, p. 97).

The difference in application of operational definitions as opposed to the operator definitions is most acute when nonequilibrium phase changes introduce new entropy generators to the Universe, suckled by a hierarchy of low-entropy mothers. Thus, the former can cover all emergent structures whereas the latter covers the ensuing steady states.

Only by knowing and understanding how chemosynthetic life first emerged and, from a branch of this life, how oxygenic photosynthesis first onset, can we grasp fully the why and how of all the mechanisms that occur in organisms and, through interactions between organisms, how organisms feed from, and back, to their coevolving environment, in ecosystems. These are the required foundations that should be made clear in the first chapters to all and any science books about organisms and their ecology. Such understanding can only come from transdisciplinary studies and cooperative research. Till now these issues have been blighted and blinkered by the hubristic claims from individual disciplines. The two concepts of O-life and S-life, along with the knowledge that overall life is an entropy generator, span a realm that cannot be accommodated in the realms of just one or two fields of study.

Acknowledgement The research described in this perspective was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and supported by the NASA Astrobiology Institute (Icy Worlds).

References

Allen JF (2010) Redox homeostasis in the emergence of life. On the constant internal environment of nascent living cells. J Cosmol 10:3362–3373

Branscomb E, Russell MJ (2013) Turnstiles and bifurcators: the disequilibrium converting engines that put metabolism on the road. Biochim Biophys Acta Bioenergetics 1827(2):62–78

Danyal K, Dean DR, Hoffman BM, Seefeldt LC (2011) Electron transfer within nitrogenase: evidence for a deficit-spending mechanism. Biochemistry 50(43):9255–9263

Hawking S, Hawking SW (1994) Black holes and baby universes and other essays. Random House, New York

Hazen RM et al (2008) Mineral evolution. Am Mineral 93(11–12):1693–1720

Hoffmann PM (2012) Life's ratchet: how molecular machines extract order from chaos. Basic Books, New York

Maret W (2016) The metals in the biological periodic system of the elements: concepts and conjectures. Int J Mol Sci 17:66. doi:10.3390/ijms17010066

Russell MJ, Kanik I (2010) Why does life start, what does it do, where will it be, and how might we find it? J Cosmol 5:1008–1039

Russell MJ, Nitschke W, Branscomb E (2013) The inevitable journey to being. Philos Trans R Soc Lond B Biol Sci 368(1622):20120254

Schrödinger E (1967) What Is life? Cambridge Univ Press, Cambridge (with a Forward by Roger Penrose (first published 1944))

Chapter 14
A Thermodynamic Account of the Emergence of Organised Matter

Gerard A.J.M. Jagers op Akkerhuis

> *"Who was right, Darwin or Carnot?" (Capra 1996, p 48).*

Abstract The preceding chapters of this book focus on complexity, evolution and life. Relatively little attention is paid to underlying mechanisms. This is the reason why the current chapter focuses predominantly on mechanisms that can explain the organisation of complex systems, either operators or interaction systems. The main causes of organisation are sought in the intrinsic motion of fundamental particles at temperatures above absolute zero, and the capacity of bonds between particles to form and break. Such processes are analysed from a thermodynamic perspective, focusing on the degradation of free energy and the occupation of accessible microstates. Both the degradation of free energy and the occupation of accessible microstates play a role during every next step in the Operator Hierarchy. Accessible microstates are furthermore used for calculating the contributions of DNA and of the brain to complexity on earth, as well as for calculating the probability that a pattern of Darwinian evolution occurs. In Sect. 14.3 relationships are discussed with existing literature.

14.1 Introduction

A large fraction of this book is dedicated to describing the Operator Hierarchy(e.g. Jagers op Akkerhuis and van Straalen 1999), and the concepts of Darwinian evolution, major transitions and life. The focus is on the identification and classification of different kinds of entities in the world, for example the different kinds of operators or interaction systems, and on analyses of patterns of Darwinian evolution. The mechanisms that can be held responsible for the formation of objects/patterns were

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_14

not addressed explicitly. To compensate for this, the current chapter focuses on thermodynamics, the science that studies the dispersal of heat/energy, and the relationship with energy and work. Thermodynamics will help to explain the processes mentioned in earlier chapters, notably the emergence of structured matter.

Thermodynamics is a large and complicated field of study. To limit the scope this chapter focuses on two major themes: (1) An overview of thermodynamics as a cause of organisation, and (2) The analysis of the Operator Hierarchy, human DNA and the human brain, and Darwinian evolution in terms of microstates.

An important concept in thermodynamics is entropy, in the sense of thermal entropy. The concept of entropy had been introduced as a measure for the dispersal of energy (Clausius 1865; Lambert 2002). The more an amount of energy is dispersed, the higher its entropy. As Boltzmann (1866) indicated, a statistical interpretation of entropy is possible if matter is viewed as representing a distribution in space of energy quanta (see also Annila 2010). As discussed for example by Lambert (1999, 2007), confusion about the concept of entropy can arise if one abandons the energetic component and only focuses on states. Approaches which do not take energy into account, and only talk about entropy as a statistical measure, are indicated as configurational entropy, positional entropy or information entropy (e.g. Shannon and Weaver 1949).

From the perspective of thermal entropy, the momentary state of a system can be described by making a picture of all the quantized units of energy in the system. Such a picture is considered as a microstate of the system. If one takes two successive pictures, each picture will represent a new microstate. A system can thus never be in more than one microstate at a time. Every microstate must be accessible via dynamics and/or transformative interactions of the objects in the system. For this reason microstates are also being referred to as accessible states. If over time, the probability of finding a system in each of its accessible states is the same, the system is said to be in equilibrium, which in the universe is a rare situation. If a potential future configuration of the system allows for more accessible states, the system is viewed as showing a gradient and as being out of equilibrium. So far, and without (large and/or long-lasting) exceptions, all measurements have shown that the universe on average changes towards future configurations that have more accessible states for quantum particles. As systems will always change in the direction of more microstates, a future situation that allows for more accessible states can be viewed as an attractor for the system (Milnor 1985).

As has been indicated by Wicken (1985) an important aspect of the use of entropy is that this measure refers to the outcome, the consequence, of a process, and not to its cause. For example if one looks at the diffusion of gas molecules, a diffused state is the outcome/result of the intrinsic motion of the molecules and the density dependent probability of collisions. On average, a particular molecule will always move in the direction of open space, because its average path-length in that direction is longest. Although an entropy viewpoint gives the impression that a gas is attracted towards a diffused state, and that attraction happens because the diffused state has the most microstates, the gas is in fact forced towards low density areas because of the intrinsic movement of the molecules of the gas.

A counterintuitive result of processes that lead to an increase in entropy is Darwinian evolution. For many people, it seems a paradox that the pattern of Darwinian evolution can be associated with increases in organisation, such as from bacteria, to protozoa, multicellular plants and conscious animals. The reason for this paradox is that, seemingly in conflict with the second law of thermodynamics, entropy seems to decrease every time that complex organisation emerges. Organised matter represents a state of relatively low entropy because the organisation limits the number of accessible energy states of the contributing particles. For example while growing, a plant increases in weight, because an increasing amount of organic matter is being synthesised. Compared to the chaotic environment the plant lives in, the organised molecules in a plant's tissues represent a local reduction of entropy. It has been shown that this paradox can be solved for open systems by focusing on the net overall entropy production in the universe (e.g. Prigogine and Stengers 1984). Now the growth of plants can be explained because it is accompanied by a net increase of entropy in the universe.

As has been advocated by several authors (e.g. Kai 1989; Swenson 1989; Chaisson 2001; Annila 2010), plants and all other organism can be viewed as devices for entropy production, in the sense that they owe their existence to the degradation of energy gradients. As a device, a plant degrades the energy in a ray of sunlight much more thoroughly, with more microstates as a result, than reflection by raindrops at the tops of clouds, or by sand in a desert. A plant uses the gradient between solar radiation and earthen temperature to fuel its physiology. A ray of sunlight that enters the plant is much warmer (about 3000 K) than the environment of the plant, say 15 °C. The difference in energy level can be used to perform work. To always reason about the same basic quantity and direction of events, Schrödinger (1944) advocated that instead of talking about organisms feeding on negative entropy, it may be preferred to say that they degrade free energy. This suggestion is followed throughout this chapter.

When the energy that was gained from a ray of sunlight finally leaves a plant, is has been transformed to low temperature heat radiation, to many randomly moving molecules of water that evaporated from the plant, to oxygen from water that was split molecularly, and to additional biomass that was produced in the plant. In fact, so much energy is used to perform work (water transport, evaporation, chemical reactions involved in maintenance), that only a minute fraction of the energy of the sunlight is turned into biomass (Styer 2008). The entropy production by plants can also be measured indirectly from the radiation that a specific surface of the earth emits, which is called the albedo of the earth. The albedo is higher above bare sand than above vegetation, indicating that bare sand reduces the energy of the sun less efficiently. The albedo is also higher above early succession ecosystems than above late succession ecosystems (Lovall and Holbo 1989; Schneider and Kay 1994, 1995; Kleidon 2009), which demonstrates that late successional ecosystems are more efficient in reducing the energy of the sun.

In the scientific literature, a broad range of viewpoints has been published on various aspects of the relationship between thermodynamics and system organisation, including: the maximum entropy production principle (Swenson 1989, 1997;

Annila 2010), the constructal law (Bejan and Lorente 2004, 2006; Bejan and Marsden 2009; Bejan and Zane 2012), the law of time and chaos (Kurzweil 1999), the chemical autocatalysis in cells as a powerful engine that drives organic life, maintenance and reproduction (e.g. Eigen and Schuster 1979; Kauffman 1986, 1993; Gánti 1971, 2003a, b; Pross 2003; Jagers op Akkerhuis 2012), the thermodynamic justification of local entropy increase in open systems (Prigogine and Stengers 1984), the viewpoint of organisation as anti-entropy (Bailly and Longo 2009), the role of the proton-motive force for the functioning of bacteria (Russell et al. 2013) and the importance of leverage and obstructions for the formation of structured matter (Lambert: http://2ndlaw.oxy.edu/obstructions.html). In addition, various studies discuss the general relationships between entropy and information (e.g. Brooks and Wiley 1986; Salthe 1993; Hunter Tow 1998; Salthe and Fuhrman 2005; Spier 1996, 2011). Now that the word information is used, it is necessary to explain what is meant with it. In this book, the concept of information is used in two ways. One way is to view information as a measure for the organisation of data/matter, such as the number of digits in a code (Shannon and Weaver 1949). The other way, which has been advocated for example by Checkland and Scholes (1990), is to view the concept of information as referring to data that can be endowed a meaning in a context.

The Operator Theory offers an interesting context for analysing possible relationships between thermodynamics and the organisation of matter. As part of such an analysis one can focus on microstates, for example as can be recognised in the construction of operatorin the operator hierarchy, and in patterns of Darwinian evolution.

14.1.1 Thermodynamics and Organisation

Every autonomous process complies with the second law of thermodynamics. This law states that free energy gradients in the universe level off towards a minimum (e.g. Boltzman 1866; Lambert 1999, 2011; Annila 2010).

Some people interpret the second law as if this would cause systems to change from organisation to chaos. However, several straightforward examples exist in which the reduction of an energetic gradient is accompanied by the formation of structure. For example in all processes of condensation matter aggregates to a lower energy state, while the energy that is produced by the process is radiated into the environment. Examples are the formation of atoms, raindrops, snowflakes and the phospholipid bilayer of the cell membrane.

Organisation may furthermore increase locally when a larger process of free energy degradation acts as the leverage for a smaller process. During the leverage process free energy is concentrated and/or the degree of organisation shows an increase (Lambert http://2ndlaw.oxy.edu/obstructions.html). At the moment, all organisms on earth thank their existence to their capacity to directly, or indirectly tap the free energy from geochemical sources, or from solar radiation.

If one uses thermodynamics to explain the formation of structure, one focuses on the formation process. However, once a structure has been formed it can in principle disintegrate as quickly as it was formed. If the speeds of the processes of formation and disintegration would be equal, one would not expect structured matter to last long. However, as Lambert (http://2ndlaw.oxy.edu/obstructions.html) has emphasised, nature is full of potential barriers acting as pawls that obstruct rapid disintegration of structures after they have formed. The following lines offer two examples of such pawls:

1. Some systems were formed as the result of condensation processes during which the heat of condensation was radiated away into the environment while the local system gained a low free energy level. Examples of such systems are hadrons, atoms, molecules and crystals. There are two reasons why these systems do not immediately fall apart after formation. Firstly, the low free energy level of these systems is stable if the system cannot easily "fall deeper" towards a still lower energy state. Secondly, energy from the environment must be transferred to the system before it can move out of its low energy pit.
2. Some systems were formed as the result of a leverage process that has pushed the object up an imaginary slide towards a higher degree of organisation. Now, a potential barrier is the only way to prevent an immediate slide-back. As has been explained by Lambert (http://2ndlaw.oxy.edu/obstructions.html), subsequent rounds of leverages and potential barriers can form ratchet-up processes that allow material organisation to increase to great height, without any conflict with the laws of thermodynamics. Ratchets also play a role in the work of Bickhard and Campbell 2003 about emergent organisation.

14.1.2 Rates of Free Energy Degradation

In principle all autonomous flows in the universe take place in the direction of a future equilibrium state. At present, the baseline for energetic equilibrium in the universe is that of the cosmic background radiation. This radiation currently has a very low temperature of 2.73 K. The cosmic background temperature still decreases as the result of the dilution of energy in an expanding universe. It has furthermore been proposed that a universe in its lowest free energy state would be filled evenly with the least complex fundamental particles, e.g. neutrinos (Annila 2010).

If the dynamics of planet earth and the universe would be in thermodynamics equilibrium, this would mean that the temperature on earth would be 2.73 K. However, the temperatures of the earth's surface and atmosphere are well above equilibrium, because of the radiation of the sun, the heat of the magma in the earth and the isolating effect of the earth's atmosphere. Temperature differences between air at the surface of the earth and at high altitudes, and temperature differences between the tropics and the poles, provide major gradients for flows of air and water.

When considering equilibration processes and their rates (e.g. Chaisson 2001, 2011) one can observe that self-organisation processes can both accelerate and delay equilibration processes. On the one hand, self-organisation processes can cause energy to become confined in fundamental particles of varying stability, and thereafter into aggregations of such particles, up to the level of molecules. Condensation processes that lead to the formation of fundamental and higher level-particles can be viewed as retarding the equilibration of free energy in the universe (Layzier 1990). On the other hand many self-organised structures can be viewed as free-energy degradation devices. For example stars and black holes produce enormous amounts of heat radiation that is dispersed in the universe. And even though they are not as big as stars, organisms are very active degradation devices, because their metabolism produces more heat per kilogram than the sun.

14.1.3 Flows and Structure in Thermodynamics

As a general narrative for the understanding of the process of free energy degradation Swenson (1988, 1989, 1997) has introduced the story of a wooden cabin in a cold mountain region. When the windows are closed, the heat in the cabin will dissipate slowly through the walls until the air outside and inside the cabin has the same temperature and equilibrium has been reached. If a window is opened, the dissipation of heat through the walls will continue, but because the additional loss of warm air through the window is faster, most of the dissipation will take place through the open window. The example of the cabin allows one to focus on two aspects.

One important aspect of Swenson's cabin is the focus on flows of energy. Swenson suggests that nature will dissipate energy gradients the fastest way possible, along the steepest gradients, combining all pathways available. This principle has been named the principle of maximum entropy production (MEP, Swenson 1988) and is equivalent to the mechanical principle of least action (Noether 1918). Kleidon et al. (2010) have indicated that when discussing the MEP principle there must be clarity about a focus on the energetic interpretation of entropy. The application of the MEP principle to organisms has been disputed, because of the theoretical assumption that when an organism would die and disintegrate, this would lead to a faster entropy increase than if the organism would maintain its structure (e.g. Volk and Pauluis 2010; Holdaway et al. 2010). However, as a test of this idea, one could kill an animal and sterilise the cadaver by means of irradiation. After irradiation, the free energy degradation rate of the now sterile cadaver has become low compared to a metabolically active organism.

The second aspect is the presence of pathways, e.g. the walls and the windows in Swenson's cabin. These walls and windows are examples of organised structures. In the example of the mountain cabin, a carpenter must invest time and energy to install the cabin and to make a window in the wall. But who in nature is the carpenter who builds a cabin and installs the windows? And what structures in nature can be considered as to represent a window in nature's cabin?

14.1.4 Operators as Windows in Nature's Cabin

Above it was indicated that Swenson (1989) used the heat-loss from a wooden cabin as an analogy for the dispersal of free energy. One aspect of the cabin analogy was the presence of a window. This window analogy will be extended here by assuming that a cabin can have different kinds of windows. If one now uses the reasoning of the Operator Theory (see Chap. 2), two major groups of kinds of windows are represented by the operators and the interaction systems. While the interaction systems are discussed in the next paragraph, this paragraph focuses on the thermodynamic aspects of the formation and functioning of the operators. And the formation processes of operators are split into two eras: the era of condensation and the era of contained dissipation. An overview of aspects of this divide has been offered by Jagers op Akkerhuis (2014).

The Era of Condensation

In the early universe, self-organisation started with the formation of fundamental particles. Subsequently, condensation processes were the reason that the fundamental particles called quarks combined to more complex particles called hadrons, of which the proton and neutron are examples. During such condensation processes the binding of the quarks caused a lower energy state, and the excess energy was radiated into the environment. As a consequence free energy was dispersed into the universe. Also when protons and neutrons form atom nuclei, binding energy is released and dispersed into the environment. Subsequently, atoms were formed as the result of electrons condensing into electron orbits around the atom nuclei, after which atoms condensed to molecules. In turn, molecules can show many different condensation reactions. One of such condensation processes, the condensation of fatty acid molecules in water, now leads to the formation of lipid bilayers. The combination of a spherically closed lipid bilayer containing (set-wise) autocatalytic reactions formed the basis for the formation of the bacterial cell. The cell, although it is contained by a membrane, represents an open system, showing an influx and efflux of material, while the processes involved in the autocatalytic chemistry allow the cell to maintain its structure.

The Era of Contained Dissipation

The moment that certain dissipative processes became contained by a membrane represents a turning point in the relationship between thermodynamics and material organisation. Before contained dissipation existed, condensation reactions were the main cause of the formation of increasingly organised objects. After the emergence of contained dissipation, systems emerged that, like watermills, tapped energy from the environment in a continuous way. While being fuelled by external sources of energy, such watermill-systems could realise growth. In some cases growth resulted in the breaking apart of the cell, hereby allowing for multiplication. And multiplication leads to a chain reaction that channels the thermodynamic gradients in the environment into the continuous (forced) production of new contained systems, which initially took the form of cells. One can also say that contained dissipation must produce new cells as long as there is an energetic gradient. Autocatalysis thus acts as a driving force behind the increase in the abundance of cells.

Multiplication will lead to increasing number of cells. If there are many cells in a limited environment, this will cause competition for resources. Some cells may even start using other cells as a resource. And competition will favour the best performing individuals, and in this way fuel the processes that lead to the pattern of Darwinian evolution. Autocatalysis thus can be viewed as an important kind of "engine" that leads to the emergence of patterns of Darwinian evolution.

14.1.5 Interaction Systems as Windows in Nature's Cabin

After having discussed the emergence of operators in the preceding chapter, it is time to discuss systems that consist of interacting operators, called interaction systems (as explained in Chap. 2). Interaction systems can be viewed as a special kind of windows in the cabin of nature taking the shape of vortices, flows and large scale aggregates, e.g. hurricanes, galaxies, stars, flames, waves, ecosystems, oceanic and atmospheric conveyor belts, water catchments, clouds, bee colonies, planets, stars, and societies.

An important law in the context of self-organisation of flow-systems of interacting operators is the constructal law (Bejan 1997). The constructal law states that "for a finite-size flow system to persist in time (to live), it must evolve in such a way that it provides greater and greater access to currents that flow through it". The constructal law subsumes a gradient that causes a flow, and an environment that the flow interacts with. Bejan and Lorente (2010) indicate that the constructal law is more general than the maximum energy production principle and that it is not a statement of optimality, end design or destiny. In Bejan and Lorente (2010) they discuss the basic assumptions of the constructal law while comparing it with 11 different statements about entropy and flow systems that can be found in the literature.

With respect to the exact phrasing of the constructal law, it was suggested in Jagers op Akkerhuis 2010 to avoid the addition of "to live" because not every form of persistence may imply a process of living. Bejan (1997) also suggested the term morphing as an indication of the dynamics of a specific flow system. The concept of morphing can be extended to flows of systems that produce generations, which can be referred to as generational morphing. Generational morphing processes can produce many patterns of events, including the pattern of branching, in which case all objects show derivation and the pattern of selection does not occur, or the pattern of Darwinian evolution, in which case the pattern of selection occurs (see also Chap. 4).

14.2 Structural and Evolutionary Microstates

14.2.1 Using Operators for the Quantification of Informational Microstates

As was discussed above, thermodynamic calculations are based on microstates. In this paragraph, a representation is created of the structures of operators in terms of informational microstates.

For an analysis of the relationship between different kinds of operators and informational microstates (hereafter referred to as microstates) the operator hierarchy is used as a foundation. For simplicity reasons, it is assumed that the branching structure of the operator hierarchy can be straightened to a complexity ladder. Using this ladder the increase of structural organisation during every step on the ladder can be linked to a dual closure, which, as explained in Sect. 2.5.3, combines a new kind of functional closure and a new kind of structural closure. For example, the cell is formed through the combination of set-wise autocatalysis (functional closure) and the membrane (structural closure).

The dual closures of the operator hierarchy can be used for creating a framework for the identification and classification of different kinds of microstates involved. The creation of this framework starts with the simplifying assumption that dual closure can be reduced to a least complex form, by hypothetically reducing the number of operators and their interactions, until further elimination would imply that the system involved would no longer meet the criteria for dual closure. Theoretically speaking, the minimum number of operators and relationships involved would be two for the functional closure, and one or more for the structural closure. While due to this simplifying approach the number of objects and relationships of every operator is reduced to a hypothetical minimum, the description of any real world configuration will generally demand the elaboration of this minimum. But a valid real-world description is not the goal here. The goal is to use the dual closure in its minimal form as a base-line for the construction of a framework that defines the kinds of dual closure, and related microstates, at the smallest scale.

As Fig. 14.1 shows, by simplifying dual closure to connections between pairs of operators, a log-linear relationship can be imagined between the number of dual closure steps and the doubling of closure-based microstates.

As a consequence of many simplifying assumptions the line in Fig. 14.1 takes the form of an exponential increase with base 2. In reality, more particles will be involved each time, and the increase will be steeper, but this only affects a quantitative aspect of the present reasoning, not the basic logic.

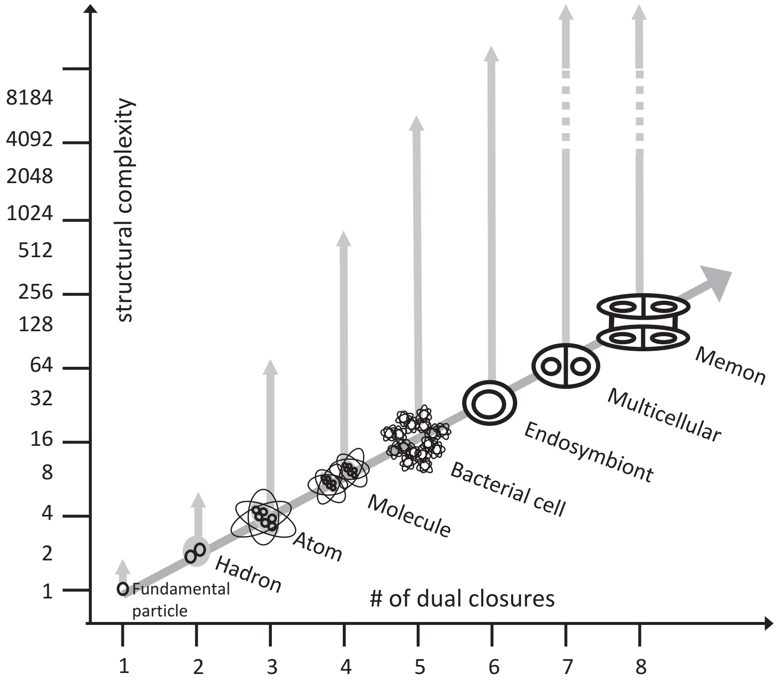

Fig. 14.1 A hypothetical representation of the least complex structures of increasingly complex operators. Every next kind of operator is assumed to be constructed of only two lower level operators. *Grey vertical arrows* offer an indication of the potential for variation in structural organisation of every kind of operator

14.2.2 Operators of the Same Kind Can Vary Markedly in Complexity

If one assumes that every next operator can be viewed as depending basically on only two preceding level operators, this results in a baseline complexity for every kind of operator. More information is required if one aims at describing the entire range of potential structures of all possible operators of a specific kind. For example the baseline complexity of an endosymbiont multicellular (such as a plant) is a structure that consists of only two cells. From this basis one can extend the approach to include all the operators of the multicellular kind that consist of three or more cells, up till large plants such as e.g. sequoia trees. In the following lines it is examined how the structure of all operators at a specific level in the Operator Hierarchy can vary from very simple to very complex.

Starting with fundamental particles, the standard model shows that science has indicated the existence of six kinds of quarks (each of which may show three different "colours") six kinds of leptons (such as the electron) and a handful of bosons (such as the photon) (Close 1983). This indicates that the number of fundamental particles may be quite limited.

As a next step, pairs of two quarks form mesons, and groups of three quarks form baryons (such as the proton and neutron). There are many combinations that can be made, resulting in a total of about 30 mesons and 80 baryons (Close 1983). While mesons are generally unstable, baryons are relatively stable. Of the baryons, single neutrons have a half-life of 15 min, while protons are almost fully stable.

Neutrons can form stable interactions with protons, resulting in the formation of structures called nucleids. There exist roughly 905 nucleids with a half-life of more than an hour. If short-lived nucleids are included in the summation, this results in a total of more than 3300 nucleids (Tuli 2005). If a nucleid is orbited by one or more electrons the resulting system is called an atom. The nucleid is now called an atom nucleus.

Next, atoms can integrate to form molecules. Now, the number of possible combinations suddenly becomes very large. Even if one focuses on a world in which no organisms are present, the number of molecules that can be constructed chemically is huge. And there is virtually no end to the number of molecules that can be constructed by organisms.

Next, the emergence of the (bacterial) single-celled operator implies that the number of possibilities becomes almost as large as the number of individual cells that are formed. The reason is that every cell with a different autocatalytic set or a different kind of membrane represents a new kind of cell.

At still higher levels, the number of possibilities increases further still. In practice, one can imagine that there may be a limit on the numbers of kinds of units that can be formed, because more complicated units are more difficult to construct, and because there will be increasing costs of maintenance. Such thoughts correspond with the existence of extremely many different realisations of the operator kind called unicellular with endosymbionts, many realisations of operator called multicellular, and a large number of realisations of the operator called neural network organisms.

As was discussed in Sect. 2.7.5 the number of realisations of a specific kind of operator, say a molecule, or a cell, may increase by the existence of technologically produced artefacts. Examples are Teflon and silicone glue (molecules), and genetically manipulated animals (cells, endosymbionts and multicellulars).

14.2.3 Potential Informational Microstates of the Human DNA and the Human Brain

The Operator Hierarchy offers a structured approach to the increase in the lower limit of the number of informational microstates related to dual closures in the range from the cell to the multicellular organism with neural network. The focus on the least complex closure configurations is one way to analyse potential informational microstates (hereafter referred to as microstates). Another way is to look in a more realistic way at the microstates of a cell and a brain. For this purpose one can compare the potential microstates of a cell in a human body with the potential microstates of the human brain. To simplify such calculations, it is assumed that the microstates of a human cell are mainly determined by the DNA in the cell.

For the above comparison a method must be identified that allows the calculation of the potential microstates of both systems. After that, the ratio of these numbers (now related to organisation and information, not to thermal entropy) can be calculated.

The human DNA in a single cell is roughly 2 m long and has 5727000000 base pairs (in order not to underestimate the value, the relatively high estimate of the National Centre for Biotechnology, Human Reference sequence from Build 33 of the Human Genome, released April 14, 2003 was used as reference). Each of these base pairs can take two forms: thymine–adenine or cytosine–guanine. The number of potential microstates of human DNA thus amounts to $2^{(5.727\times10^{9})}$ which equals $10^{(1.724\times10^{9})}$. The actual DNA of an individual human will represent a single specific realisation out of all these potential states. And because the focus here is on human DNA, most of the coding will be equal if one compares one human being with another, such that only a minor fraction of the coding, much less than 1 %, will differ between two randomly chosen individuals. In principle one could also go one step beyond the number of potential microstates by coupling organisation to the informed-ness of the DNA, by focusing on the non-random patterning of the DNA, and its relationship with phenotypic properties. In the attempt, one would have to take into account that DNA sequences may imply coding at various levels (single base pairs, triplets, sequences of triplets, redundancy etc.), for which reason there will not be a simple a priori calculation for this informed-ness. To keep things simple, the focus is on the potential number of informational microstates of the entire DNA as an approximation of the maximum number of possibilities.

Compared to DNA, how many potential microstates does the human brain have? To calculate this number, one must analyse the basic structure of the brain. There exist no exact measurements, but scientific estimates amount to 80–120 billion nerve cells ($80–120\times10^{9}$), each of which being on average connected to 7000 other cells (Herculano-Houzel 2009). This results in a rough estimate of $100\times7000\times10^{9}=7\times10^{14}$ connections (seven hundred thousand billion). Normally, every synapse can adapt the intensity of its chemo-electrical interaction with a specific neuron in a continuous way. If this situation is simplified to ten fixed levels, and if additional possibilities of inhibition or excitation are disregarded, this leads to a conservative estimate for the number of possible microstates of $10^{(7\times10^{14})}$, which is a number that is represented by a digit 1 followed by seven hundred thousand billion zeros.

Based on the above calculations a rough comparison can now be made of the potential state spaces of a human DNA and a human brain. The human DNA has 5727000000 base pairs, which allow for $10^{(1.724\times10^{9})}$ microstates. And the human brain has 7×10^{14} connections, which allow for $10^{(7\times10^{14})}$ microstates. With very large numbers like these, it is difficult to get an impression of the relative sizes. As a simple way of comparison, one can divide the numbers of potential microstates of the brain and the DNA. To make such a calculation simple, one can use rounded-off numbers, assuming a brain with $10^{(10^{14})}$ microstates, and DNA with $10^{(10^{9})}$ microstates. The proportion of the microstates requires that one divides these numbers. Since division of powers equals a subtraction, the result is: $10^{(10^{14}-10^{9})}$, which equals $10^{(10^{9}(10^{5}-1))}$, which is approximately equal to $10^{(10^{9}(10^{5}))}$ and thus to $10^{(10^{14})}$. This number consists of a digit 1 that is followed by hundred thousand billion zeros. This approximation shows that the number of potential microstates of the human brain is of an entirely different dimension than the number of potential microstates of the human DNA.

14.2.4 A Thermodynamic Perspective for Analysing Darwinian Evolution

In Chaps. 4 and 6 a pattern-based definition of Darwinian evolution was suggested. The pattern at the smallest scale minimally includes a parent, and two offspring. The concepts of parents and offspring are used here, not because the current reasoning is limited to biology, but because it is easier to in the following explanation use well-known concepts, such as parent and offspring, instead of the generally valid concepts of original and derived object that were introduced in Chap. 4. For the pattern of selection to emerge, only one of the two offspring must realise derivation, such that derivation is differential. A link between the pattern of Darwinian evolution and thermodynamics can now be created by suggesting that every specific pattern of realisation/failure of derivation can be viewed as a potential informational microstate. By investigating the number of potential informational microstates, and the chances that they are realised, it can for example be researched whether or not all the evolutionary microstates represent an attractor for the system, compared to all possible microstates.

To link evolution and thermodynamics, an inventory was made of all the patterns of selection that through permutations can be constructed if one focuses on a parent that has 1, 2, 3 or 4 offspring, each of which may, or may not realise derivation. The following reasoning makes use of two assumptions: (1) every offspring has an equal probability to inherit either property A or B, and (2) an organism with property A or B has a 50 % chance to realise or not realise derivation (see discussion about failure of derivation in Sects. 4.3.5 and 4.4). These assumptions result in what can be viewed as a null-hypothesis.

Figure 14.2 offers an example of all the tables with potential microstates that can be imagined if a parent has either 1, or 2, or 3 or 4 offspring. In each case, the combinations (Comb.) of a number of A and/or a number of B offspring is indicated together with the probability (Prob.) of this combination. The potential microstates that can be realised are elaborated for numbers of A and/or B offspring. Whether a

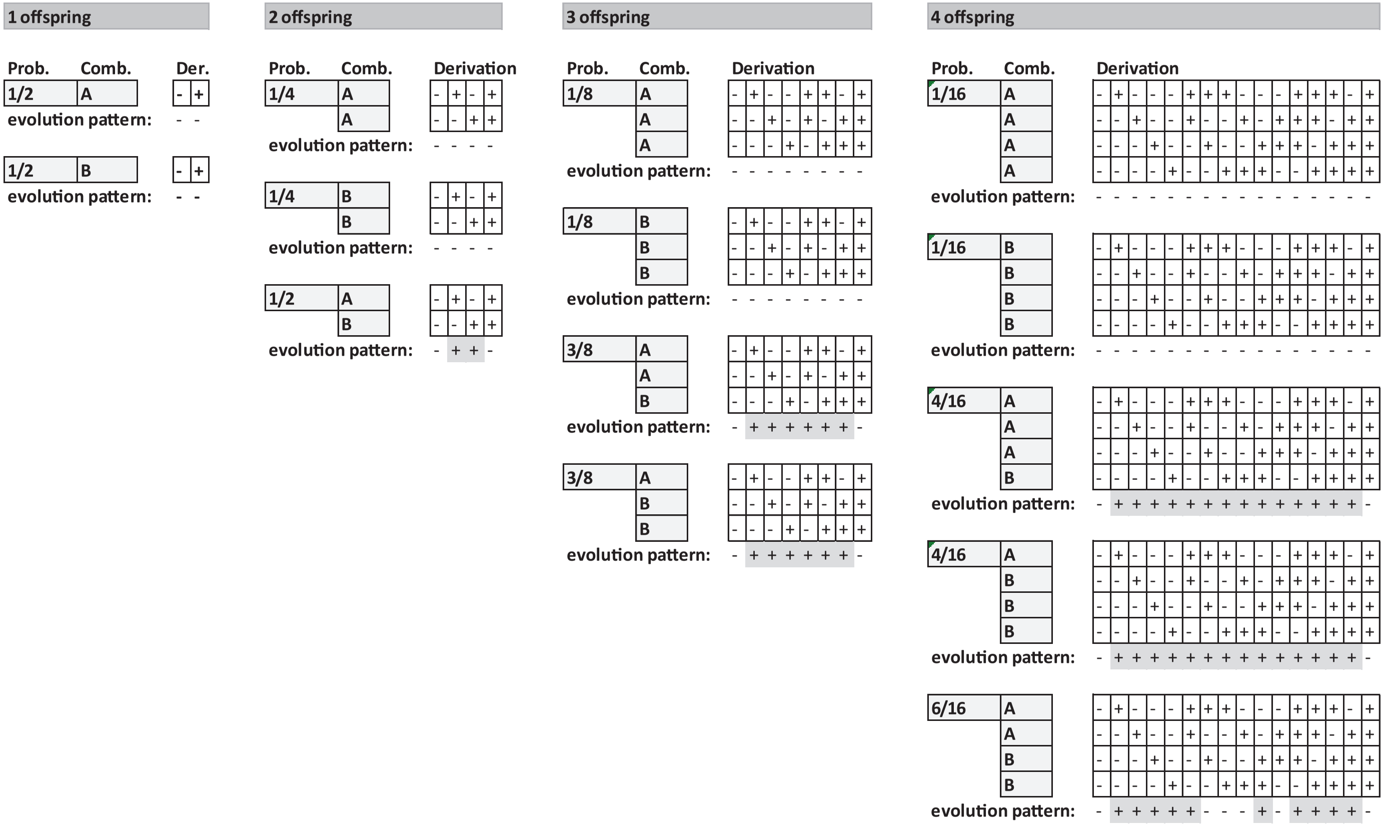

Fig. 14.2 Predicting the chance that a pattern of Darwinian evolution occurs in the offspring generation if a parent produces 1, 2, 3 or 4 offspring. A and B are derived object. As a null-hypothesis A and B have a 50 % chance to differ in a single property and have a 50 % chance that they realise derivation. Each derivation table offers an example of all possible successes/failures of derivation (viewed as microstates). In each derivation table "+" indicates successful derivation, and "–" failure of derivation. + = evolutionary pattern. Prob. = the chance that the permutations of A and B occur in the derived generation. Comb. = the number of A and B objects in the derived generation

microstates represent an evolutionary pattern is indicated at the bottom of every microstate.

From the information in Fig. 14.2 the following probabilities for an evolutionary pattern can be calculated:

For one offspring the chance of a Darwinian pattern is: 0

For two offspring the chance of a Darwinian pattern is: $(2/4)\times 0+(2/4)\times(2/4)=0.25$

For three offspring the chance of a Darwinian pattern is: $(2/8)\times 0+(6/8)\times(6/8)=0.5625$

For four offspring the chance of a Darwinian pattern is: $(2/16)\times 0+(8/16)\times(14/16)+(6/16)\times(10/16)=0.672$

These calculations demonstrate that a larger number of offspring leads to a higher chance that the pattern of Darwinian evolution is realised given the model conditions. The goal of this section was limited to a quick glance at calculations of the probability that evolutionary patterns occur. The ideas offered can serve as a basis for more elaborate calculations, for example by taking into account the probability distribution of the number of offspring a parent will have. Another elaboration may involve the impact of unequal chances of a parent giving birth to an A or B kind of offspring, and/or of unequal chances that the offspring of kind A or B realise derivation.

14.3 Discussion

This chapter focuses on a thermodynamic account of the emergence of organised matter. This account shows two aspects. On the one hand, one can observe the degradation of locally and temporarily existing free energy gradients, while on the other hand energy has been captured in matter of increasingly “condensed” kinds of organisation, from quarks, to hadrons, atoms and molecules. The below text elaborates on some of the subjects that were handled in this chapter and relates them to additional literature.

14.3.1 Mechanisms that Scaffold the Formation of Structured Matter

Based on a review of existing literature, a broad range of mechanisms could be identified where the increase in material organisation is accompanied by the degradation of free energy, including: condensation, leveraging, ratchet and pawl mechanisms, and forced multiplication accompanied by competition. In relation to such processes, it is relevant that many observations indicate that the formation of complex structure is associated with the fastest possible degradation of momentary gradients (Noether 1918; Lotka 1922, 1945; Swenson 1997; Schneider and Kay 1994a, b; Kleidon 2009; Annila 2010; Bejan and Lorente 2010).

14.3.2 How Can Complexity Increase During Darwinian Evolution?

The existence of organisms, their reproduction and the emergence of the pattern of Darwinian evolution, are all driven by the explosive force of contained autocatalysis. When hearing the word autocatalysis, a thought that may come to mind is that of a set of catalytic molecules which transform substrate molecules to, together, produce all the catalytic molecules in the set. However, in bacteria, a large part of the catalytic reactions are driven by a gradient of protons that is maintained over the membrane (e.g. Pross 2003; Lane 2010; Branscomb and Russell 2013). The driving force of autocatalysis explains why organisms can maintain their structure. And, due to contained autocatalysis, organisms can in principle invest any amount of energy in the increase of their organisation. Such investment requires of course that sufficient external gradients are available. The maintenance of their structure implies that organisms continuously degrade free energy gradients. For this reason, autocatalysis forms the link between the existence of organisms and the maximum energy production principle. The earliest steps towards unicellular organisms presumably will have involved condensation reactions that created a membrane that surrounded and contributed to primitive autocatalytic reactions. Once contained autocatalysis existed, it offered a basis for growth, and potentially also for multiplication. In turn, multiplication leads to competition, because the organisms lived in a finite environment where they had to compete for finite resources. In a competitive environment, it is important to gain access to resources and to dominate them, while avoiding to be used as a resource. Together such properties create the capacity that has been called resource dominance (Jagers op Akkerhuis and Damgaard 1999). When there is competition for resources that are finite, and assuming that evolutionary adaptation over generations is possible, the trade-offs between size, complexity of organisation and the capacity for reproduction will become the main determinants of resource dominance.

14.3.3 The Distribution of Objects of Differing Complexity in the Universe

As a basis for the quantification of levels of organisation, this study has focused on the operator hierarchy. For every level in the operator hierarchy it was discussed how one can estimate the number of operators of all the sub-kinds that potential can be found at that level (Fig. 14.1). For example the kind of operator called atom has all the atoms in the periodical system as its sub-kinds. The number of representatives per kind of operator shows an optimum that is the result of an increase in possibilities for organisation in the direction of the higher level operators, and a decrease in the possibilities because of a large size and resource requirements. Meanwhile, when Märkelä and Annila (2010) studied the sizes of entities that contribute to energy transduction they found a Poisson-like distribution for size/organisation. The two approaches are different, but seem to lead in the same direction. A reason that the results are not identical may also be that the operator hierarchy selectively includes operators in its reasoning, while the approach of Mäkelä and Annila (2010) seems to make no assumptions about the kinds of organisation of the entities included, including for example stars, horses, cars and bacteria alike, as these all transduce energy.

14.3.4 Contribution of the Brain to Biodiversity

Using conservative calculations the potential number of informational microstates of the human DNA and the human brain were assessed and compared. The results of such calculations may have consequences for discussions about the biodiversity that can be found on earth. With respect to biodiversity the convention on biological diversity (United Nations 1992) indicates that: "Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems". The biodiversity literature does not generally seem to interpret "variability among living organisms" in a way that this would include the variability of neural networks. Meanwhile, the present calculations strongly suggest that the potential number of microstates of the (human) DNA is minute compared to the number of microstates of the (human) brain. Although further work on this topic may be required before any conclusive statements can be made, the large differences in state spaces may well indicate that the contribution of neural biodiversity to the overall biodiversity of planet earth forms a neglected aspect of biodiversity that, when included, may have a marked effect on current debates.

14.3.5 Thermodynamics of Darwinian Evolution

A link was suggested between Darwinian Theory and thermodynamics by focusing on the number of informational microstates in the distribution of the realisation or the failure of derivation. As a general rule the new approach suggested that the chances for a Darwinian pattern will increase with the number of offspring. As the production of offspring is costly in terms of energy and nutrients, a high capacity for evolution through many offspring will show a trade-off with the need to produce smaller offspring.

14.4 Conclusions

This chapter suggests the following conclusions:

1. The forming of complex matter, both operators and interaction systems, takes place because of, and not despite, the degradation of free energy gradients.
2. If systems would disintegrate as rapidly as they would form, complex matter would not persist. Therefore the existence of complex matter must be viewed as the result of continuous flows (such as in the case of a whirlwind) and/or as the result of ratchet and pawl mechanisms (such as represented by the membrane that surrounds a cell).
3. The number of potential informational microstates of a human brain is very, very large. Because of this, it may be worthwhile to consider the contribution of human individuals to global biodiversity.
4. A new methodology was offered for calculating the chances that the pattern of Darwinian evolution occurs.

References

Annila A (2010) All in action. Entropy 12:2333–2358

Bailly F, Longo G (2009) Biological organization and anti-entropy. J Biol Syst 17:63–96

Bejan A (1997) Advanced engineering thermodynamics. Wiley, New York

Bejan A, Zane JP (2012) Design in nature. Doubleday, Toronto

Bejan A, Lorente S (2004) The constructal law and the thermodynamics of flow systems with configuration. Int J Heat Mass Transf 47:3203–3214

Bejan A, Lorente S (2006) Constructal theory of generation of configuration in nature and engineering. J Appl Phys 100:041301. doi:10.1063/1.2221896 (27 pages)

Bejan A, Marsden JH (2009) The constructal unification of biological and geophysical design. Phys Life Rev 6:85–102

Bejan A, Lorente S (2010) The constructal law of design and evolution in nature. Philos Trans R Soc B 365:1335–1347

Boltzmann L (1866) Üher die mechanische Beduetung des Zweiten Hauptsatzes der Wärmetheorie. Wiener Berichte 53:195–220

Bickhard M, Campbell D (2003) Variations in variation and selection: The ubiquity of the variation-and-selective-retention ratchet in emergent organizational complexity. Found Sci 8:215–282

Branscomb E, Russell MJ (2013) Turnstiles and bifurcators: the disequilibrium converting engines that put metabolism on the road. Biochim Biophys Acta 1827:62–78

Brooks DR, Wiley EO (1986) Evolution as entropy. Toward a unified theory of biology. University of Chicago Press, Chicago

Capra F (1996) The web of life: a new scientific understanding of living systems. Anchor books, New York

Chaisson EJ (2001) Cosmic evolution: the rise of complexity in nature. Harvard University Press, Cambridge

Chaisson EJ (2011) Energy rate density. II. Probing further a new complexity metric. Complexity 17:44–63

Checkland P, Scholes J (1990) Soft systems methodology in action. John Wiley & Sons Ltd, Chichester, West Sussex, England

Clausius R (1865) The mechanical theory of heat—with its applications to the steam engine and to physical properties of bodies. John van Voorst, London, MDCCCLXVII

Close F (1983) The cosmic onion: quarks and the nature of the universe. Heinemann Educational, London

Eigen M, Schuster P (1979) The hypercycle: a principle of natural self-organization. Springer, New York

Gánti T (1971) The principle of life (in Hungarian). Gondolat, Budapest

Gánti T (2003a) Theoretical foundation of fluid machineries, vol 1, Chemoton theory. Kluwer, New York

Gánti T (2003b) Theory of living systems, vol 2, Chemoton theory. Kluwer, New York

Herculano-Houzel S (2009) The human brain in numbers: a linearly scaled-up primate brain. Front Hum Neurosci. doi:10.3389/neuro.09.031.2009

Hunter Tow D (1998) The future of life: meta-evolution. A unified theory of evolution. Xlibris, Corp., Lewiston, NY

Holdaway RJ, Sparrow AD, Coomes DA (2010) Trends in entropy production during ecosystem development in the Amazon Basin. Philos Trans R Soc B 365:1437–1447

Jagers op Akkerhuis GAJM (2010) Towards a hierarchical definition of life, the organism and death. Found Sci 15:245–262

Jagers op Akkerhuis GAJM (2012) The pursuit of complexity. The utility of biodiversity from an evolutionary perspective. KNNV, Utrecht

Jagers op Akkerhuis GAJM (2014) General laws and centripetal science. Eur Rev 22:113–144

Jagers op Akkerhuis GAJM, Damgaard CF (1999) Using resource dominance to explain and predict evolutionary success. Oikos 87:609–614

Jagers op Akkerhuis GAJM, van Straalen NM (1999) Operators, the Lego-bricks of nature: evolutionary transitions from fermions to neural networks. World Futures 53:329–345

Kauffman SA (1986) Autocatalytic sets of proteins. J Theor Biol 119(1):1–24

Kauffman SA (1993) The origins of order: self-organisation and selection in evolution. Oxford University Press, Oxford (709 pp)

Kay JJ (1989) A thermodynamic perspective of the self-organization of living systems. In: Ledington PWJ (ed), Proceedings of the 33rd Annual Meeting of the International Society for the System Sciences, Edinburgh, vol 3. pp 24–30

Kleidon A (2009) Nonequilibrium thermodynamics and maximum entropy production in the Earth system. Applications and implications. Naturwissenschaften 96:653–677

Kleidon A, Yadvinder M, Cox PM (2010) Maximum entropy production in environmental and ecological systems. Philos Trans R Soc B 365:1297–1302

Kurzweil R (1999) The age of the spiritual machines. When computers exceed human intelligence. Viking, New York

Lambert FL (1999) Shuffled cards, messy desks, and disorderly dorm rooms—examples of entropy increase? Nonsense! J Chem Educ 76:1385–1387

Lambert FL (2002) Entropy is simple, qualitatively. J Chem Educ 79:1241–1246

Lambert FL (2007) Configurational entropy revisited. J Chem Educ 84:1548–1550

Lambert FL (2011) Entropy in general chemistry. Retreived from http://entropysite.oxy.edu/wiki_entropy.html

Lane N (2010) Why are cells powered by proton gradients? Nature Educ 3:18

Layzier D (1990) Cosmogenesis. The growth of order in the universe. Oxford University Press, Oxford

Lotka AJ (1922) Contribution to the energetics of evolution. Proc Natl Acad Sci U S A 8:147–155

Lotka AJ (1945) The law of evolution as a maximal principle. Hum Biol 17:167–194

Lovall JC, Holbo HR (1989) Measurements of short term thermal responses of coniferous forest canopies using thermal scanner data. Remote Sens Environ 27:1–10

Märkelä T, Annila A (2010) Natural patterns of energy dispersal. Phys Life Rev 7:477–498

Milnor J (1985) On the concept of attractor. Comm Math Phys 99:177–195

Noether E (1918) Invariante Variations probleme. Nachr D König Gesellsch D Wiss Zu Göttingen, Math-phys Klasse 1918:235–257

Prigogine I, Stengers I (1984) Order out of chaos. Man's new dialogue with nature. Bantam, New York

Pross A (2003) The driving force for life's emergence: kinetic and thermodynamic considerations. J Theor Biol 220:393–406

Russell MJ, Nitschke W, Branscomb E (2013) The inevitable journey to being. Philos Trans R Soc Lond B Biol Sci 368(1622):20120254

Salthe SN (1993) Development and evolution: complexity and change in biology. MIT, Cambridge, MA

Salthe SN, Fuhrman G (2005) The cosmic bellows: the big bang and the second law. Cosmos Hist 1:295–318

Schneider ED, Kay JJ (1994) Life as a manifestation of the second law of thermodynamics. Math Comput Model 19:25–48

Schneider ED, Kay JJ (1995) Order from disorder: the thermodynamics of complexity in biology. In: Murphy MP, O'Neil LAJ (eds) What is life: the next fifty years. Reflections on the future of biology. Cambridge University Press, Cambridge

Schrödinger E (1944) What is life? Cambridge University Press, Cambridge

Shannon CE, Weaver W (1949) The mathematical theory of communication. University of Illinois Press, Chicago

Spier F (1996) The structure of big history: from the big bang until today. Amsterdam University Press, Amsterdam

Spier F (2011) Big history and the future of humanity. Wiley Blackwell, Malden, MA

Styer DF (2008) Entropy and evolution. Am J Phys 76:1031–1033

Swenson R (1988) Emergence and the principle of maximum entropy production: multi-level system Meeting of the International Society for General Systems Research, 32. Theory, evolution, and non-equilibrium thermodynamics. Proceedings of the 32nd Annual Meeting of the International Society for General Systems Research, 32

Swenson R (1989) Emergent attractors and the law of maximum entropy production: foundations to a theory of general evolution. Syst Res 6:187–197

Swenson R (1997) Autocatakinetics, evolution, and the law of maximum entropy production: a principled foundation toward the study of human ecology. Adv Hum Ecol 6:1–46

Tuli JK (2005) Nuclear wallet cards, 7th edn. Brookhaven National Laboratory, US National Nuclear Data Center, Upton, NY

United Nations (1992) Convention on biological diversity. United Nations, New York

Volk T, Pauluis O (2010) It is not the entropy you produce, rather, how you produce it. Philos Trans R Soc B 356:1317–1322

Wicken JS (1985) Thermodynamics and the conceptual structure of evolutionary theory. J Theor Biol 117:163–383

Chapter 15
The Road to a Measurable Quantitative Understanding of Self-Organization and Evolution

Georgi Yordanov Georgiev and Atanu Chatterjee

Abstract This book has discussed some of the most important aspects in the current state of the sciences of complexity, self-organization, and evolution. A central theme in this field is the search for mechanisms that can explain the self-organization of complex systems. The quest for the main guiding principles for causal explanations can be viewed as a very timely and central aspect of this search. This book is devoted to such topics and is a necessary read for anyone working at the forefront of complexity, self-organization, and evolution. As an addition to the lines of reasoning in this book, we focus on a quantitative description of self-organization and evolution. To create a measure of a degree of organization, we have applied the Principle of Least Action from physics. Action for a trajectory is defined as the integral of the difference between kinetic and potential energy over time. This principle states that the equations of motion in nature are obeyed when action is minimized. In complex systems, there are constraints to motion that prevent the agents from moving along the paths of least action. Using free energy, those agents do work on the obstructive constraints to minimize them, in order to approach their natural state of motion given by the principle of least action. This is the process of self-organization. Therefore, the decrease in the amount of action for an agent along its path is a numerical measure for self-organization. This increase of action efficiency is a quantitative measure for the increase in organization and corresponding evolutionary level of the system. The least action state is the attractor for self-organization, and is achieved through feedback loops between the characteristics in complex systems. In our view the principle of least action applied to complex systems can introduce time dependence in nonequilibrium thermodynamics.

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DOI 10.1007/978-3-319-43802-3_15

15.1 Introduction, the Principle of Least Action

In our research, where we work toward a common definition of life, quantity of organization, evolutionary stages, or levels of complexity, we use a unifying concept in which time and energy are the fundamental quantities. In physics, all of the equations of motion exist, when the product of energy and time for a chosen trajectory is a minimum. This relationship is also known as the Principle of Least Action. The fundamental nature of this principle allows all the conservation laws and equations of motion in all branches of physics, from Classical Physics to General Relativity and Quantum Mechanics, to be derived from it (de Maupertuis 1750; Georgiev and Georgiev 2002; Ville et al. 2008).

In physics, action is the integral of the Lagrangian, over time. The Lagrangian is the difference between the kinetic and potential energy at each instant for a trajectory. In a case where no potentials are present, the integral is of the kinetic energy over time. If the kinetic energy is a constant during a process, the integral boils down to the product of the kinetic energy and time. Thus, the units of action are [Joules*Seconds]. In nature, processes occur only when action is minimized. To clarify why action is minimized but not the energy or time separately, let us do a mental experiment. If only energy is minimized, the limit of that is zero; therefore the result is that motion ceases. There are many examples of this, one of which crystallization. In such a case, the system settles in a potential minimum and is not dynamic. It does not have flows of any kind, and does not continue its self-organization. It is in thermodynamic equilibrium, which is exactly the opposite of the definition of complex self-organizing systems. Time is excluded in such equilibrium thermodynamic states. Minimizing only time, which at its limit is zero for a process, leads to a paradox contradicting the theory of relativity, which is that the speed of an object needs to be infinitely fast. Even if we take the limit of the speed of light, as the maximum speed in nature, this will require an infinite amount of energy, which forbids such minimization. Therefore in physics time and energy are in balance with each other, as their product is minimized, which is the Principle of Least Action.

15.2 Action Efficiency

Since action as a fundamental quantity can describe all of the occurrences in nature, there is no reason to search for new laws that determine the functioning of complex systems. We propose that measuring the average action efficiency for all processes in a complex system can be used to measure the amount of organization in it. The more action efficient a system is, the closer it is to the natural state of motion, the state of least action, the more highly organized it is. When viewed from this perspective, a system is more organized when it has a lower average action per event inside the system. This we view as synonymous with a higher evolutionary state.

Using action efficiency we can compare two systems, and find which one has more organization, which one is at a higher evolutionary state, and the process of evolution itself becomes a measurable process that is linked to the increase in action efficiency. If we use action efficiency as a measure of the organization of a system, we do not need to use qualitative, descriptive, and vague definitions of organization, but have one number associated with the amount of it. Thus, we can finally have numbers on the evolutionary *Y*-axis for the amount of organization in a system, and assuming that the *X*-axis represents time, equations that connect the two. We can calculate exactly the rates of evolution and predict what the evolutionary value of action efficiency will be at a certain time in the future. Evolution here is understood broadly as self-organization independent of the substrate, starting from particles, atoms, molecules, organisms and ending with our society and computing systems.

Based on the principle of least action we could gain an idea about how and why self-organization progresses, and about its time dependence. Self-organization occurs because in complex systems, the agents search for their natural state of motion, which is the one with least action, and which is the final attractor state of the system. Because there are many obstacles to that motion, those agents need to do work on those obstructive constraints to minimize them to minimize the action for their trajectories. This is the long process of "Evolution." If there was no time dependence, complex systems would have had the ability to magically and in the blink of an eye self-organize toward the highest developmental state, hereby eliminating evolution as a process.

15.3 Positive and Negative Feedback Loops

To understand the mechanism of self-organization, we concluded that decrease of average action does not happen in isolation, but that it is coupled to the changes in other quantities, such as the total amount of action in the system, the Free Energy Rate Density (FERD), the number of elements, their density, the total number of events and we are searching for more dependencies. The change in one of those characteristics happens in proportion to all others. All of them change in lockstep. For physical systems, we are working on finding those proportional relations. We term those parameters interfunctions, because of the mutual dependence of one of them on all other characteristics in the positive feedback loop between all of them. Measuring any one of those interfunctions provides information about all the rest of them, including the action efficiency for the system and therefore its level of organization, evolutionary stage, and the rate of increase in organization. In comparison to biological systems, the action efficiency is relatively more accessible for measurements in physical, chemical, and technological systems (Georgiev et al. 2015).

The notion of "circularity/closure," as discussed in Jagers op Akkerhuis (2008) and Chap. 2 of this book also relates to our perspective on the positive and negative feedback loops between the interfunctions in self-organizing systems that increase their action efficiency and evolutionary hierarchy (Chatterjee 2015). In our view, without those loops, it is impossible for a complex system to self-organize, as it will violate physical laws. For example, to overcome larger obstructive constraints to motion, and to minimize average action further, a system needs larger energy gradients and more elements to group in the existing flow channels in the system and do larger amounts of work on the constraints (Bejan and Zane 2012). Otherwise, the system cannot self-organize and will stay forever at the existing action efficiency state, as long as the energy gradients are not increased. On the other hand, to allow larger energy gradients and larger number of agents to be transmitted through the system, it needs more efficient flow networks to prevent that events such as jamming occur, leading to the destruction of a system. Therefore, action efficiency, energy gradients, and number of elements need to grow in small steps as each of them leads to the growth of the other, in a circular fashion, which is represented by a positive feedback loop. Those steps are within certain limits within which the system remains stable—homeostatic limits. The parameters of a system cannot deviate outside those homeostatic limits, which introduces a negative feedback in the model for self-organization. If there were no negative feedback between the interfunctions and their homeostatic levels, any one of the interfunctions would grow by itself, reaching extremely high values, when the rest of the interfunctions remain at low values. In that case, we would observe a system becomes more and more organized, without growing in FERD or number of elements, or a system that has extremely high FERD but very low action efficiency. Those cases are not observed in nature. Zooming in on evolutionary trends we see those negative feedback oscillations in the fine grained structure of the exponential curve of increase of action efficiency (Georgiev et al. 2015) and our goal now is to fit them to the model of positive feedback loop between the parameters of complex systems, with negative feedback loops between the parameters and their homeostatic values. We termed the study of self-organization, development, and evolution using those approaches, Devology, standing for Development, Evolution, and Logos (Georgiev et al. 2016).

15.4 Mechanisms of Self-Organization

After we have settled on a definition for organization in a complex system, we can continue discussing specifics about how the action efficiency increases. Guided by the equations of motion, agents in self-organizing systems find the paths of least action, forming the configuration of the system. Generally, in evolved systems this results in a flow network with a fractal topology and scale-free properties. Fractal topology implies self-similarity between scales. Scale-free networks with clustering naturally have a hierarchical organization, because the nodes with more connections have more influence in the network than nodes with fewer connections (Barabási et al. 2003).

Hierarchical organization is particularly common in biology. Ecosystems, food webs, gene regulatory networks, protein-protein interaction networks are all examples of hierarchically organized systems. Also, the construction of organisms exhibits a hierarchy of increasingly complex operators through first-next possible closures (Jagers op Akkerhuis 2008, 2012). The emergence of hierarchy and the evolution of self-similar topology cause complexity to increase, both structurally and functionally, through creation of flow channels, their branches and tributaries. To reduce average action, different parts of complex systems specialize in performing different functions, e.g., organs in organisms and organisms in ecosystems. In the whole system, such specialized structures are connected by scale-free flow networks. Both quantities, the properties of the flow networks and the degree of specialization, are measurable and therefore very useful to correlate with the interfunctions, such as the average action efficiency which is the degree of organization. In the broader view, these and other attributes are universal and trans-disciplinary.

The relationship of self-organization and time is dictated by the Principle of Least Action and the interactions between the agents of the system and the obstructions that prevent those agents from pursuing their least action paths. By doing work on them the agents minimize the constraints to motion and create the flow networks and the organization in those systems. The configuration of those constraints determining the average least action structure of the system can be measured in bits of information, and the more information is recorded in the structure of the system, the more efficient the flow channels and the level of organization in the system. Correlated to action efficiency and organization, information may be another interfunction connected to the rest, and growing exponentially in time. As a model system for testing some of the above relationships, we studied the core processing unit (CPU) of computing systems. We correlated the action efficiency to the total action and the distance from thermodynamic equilibrium that was measured in terms of the Free Energy Rate Density (Georgiev et al. 2015, 2016; Chaisson 2001, 2011). We have measured that all interfunctions grow exponentially in time and are in mutual power law relations, due to the positive feedback between them, matching well with the data (Georgiev et al. 2015, 2016). Because of these proportionality relationships, one can use information about the Free Energy Rate Density in a system for calculating the total amount of action and the average action efficiency, which in our definition is referred to as the quantity of organization in the system. The power law relationships between the interfunctions correlate them at any stage of self-organization and evolution. This will allow finding the level of organization in certain systems where it is difficult to measure directly, such as in biological ones (Heylighen 1999).

15.5 Principle of Least Action and Entropy

By its very nature, the Principle of Least Action is closely related to the Second Law of Thermodynamics. The Second Law states that for a closed system, the state in which all possible microstates are equally likely can be viewed as an attractor. Such a state is also indicated as the equilibrium state, or the maximum entropy state (Chatterjee 2015; Lucia 2015). If one applies the Principle of Least Action for a closed system the entropy is maximized, because all points in the system are equally probable to be start and endpoints for the trajectories and also all of them need to be visited by the agents of the system. However, when the system is open it has sources and sinks that represent the new start and endpoints for the trajectories of the agents. The total number of possible trajectories for the agents through an open system is smaller than that of a closed system. Statistically, this is equivalent to lower internal entropy. This is similar to a situation where hot air will randomly distribute heat in a closed room, whereas the same heat will travel along a specific trajectory if the doors of the room are opened, reducing the number of possible states and the entropy of the air molecules. Heat can now enter the system through one door and leave it through the second door. While one door acts as a source and the other as a sink, the channeled flow lets the heat pass through the system and allows it to dissipate into the surrounding.

Another example of channeled flow is represented by Benard cells, which are toroid convection flows that form in a thin layer of fluid when this is cooled from above and heated from below. As long as the fluid is not heated or cooled, the fluid has equal temperature and the molecules have equal probability to visit any given point in the fluid. At an equal temperature, the entropy of the fluid is at its maximum, and entropy production in the environment is close to zero. If the fluid is heated from below, it forms flow channels, the so called Benard cells that transport the heat toward the cooled upper surface. The confinement of the molecules inside the Benard cells reduces the possible microstates for the molecules and the entropy inside the system. If the temperature difference is increased, more flow channels form, which further reduces the number of possible states for the molecules. Thus, a Free Energy Rate Density increase is associated with more flow channels and with a reduction in the internal entropy of the system corresponding to fewer accessible microstates. While the second law focuses on energy dissipation, and an increase of external entropy, the principle of least action offers information about the trajectories for heat dissipation, the decrease of internal entropy, and the exact timing of energy dissipation.

15.6 Self-Organization

From a universal perspective entropy is expelled toward the surroundings by a rate that exceeds the internal entropy decrease. Self-organization is driven by energy dispersal and the internal organization in complex systems facilitates that process. Paradoxically, an increase in the potential for energy dispersal demands an increase in internal organization, such that the internal flow networks have higher ability to conduct energy. High capacity for the production of external entropy demands a highly organized system, thus low internal entropy. This means that systems self-organize because they obey physical laws, not because they defy them. In this sense, self-organization is a lawful process as inevitable as the free fall of an object in gravity, and is expected to occur anywhere where conditions allow it. Self-organization thus represents a natural and spontaneous process of internal entropy decrease.

15.7 Time Dependence of Thermodynamics

With the above we offer a correct but still incomplete description of the processes in thermodynamics. What is missing in this description is time. It is one thing to say that energy will get dispersed, but another to determine how fast. It would make a major difference if the same energy dispersal would happen in a single nanosecond or during the lifetime of the universe. Generally, however, events neither are that fast or that slow. Thus, when we describe self-organizing systems, time matters and equilibrium thermodynamics is insufficient in providing that information.

But how can nonequilibrium thermodynamics be adapted to include time dependence? We do not need to venture very far for equations that include time in the descriptions of dynamical processes. The motion of all objects has been described by classical and quantum mechanics using time-dependent equations, and all other branches of physics, starting with electrodynamics, relativity, optics, and others explicitly depend on time. We just need to introduce this dynamic viewpoint into equilibrium thermodynamics, to turn it into nonequilibrium, and to model how much time it will take for energy to disperse and for self-organization to occur (Kauffman 1993; Annila and Salthe 2010).

While it may seem a daunting task to squeeze all those enormous branches of physics into one equation, we argue that one should not forget that all possible equations of motion in all possible branches of physics, all conservation and symmetry laws have been derived from one and the same principle, namely—the Principle of Least Action. Therefore, it can be expected that the application of this principle to the processes of self-organization may result in the equations of motion of agents in self-organizing systems, and may inform us about the preferred paths of agents, about what is the flow network structure of the system accommodating those paths, and about the exact time that may be needed for this to happen. A combination of such aspects would yield the dynamics of complex systems and the rates of self-organization. Additionally, the inclusion of time in our description may convert this field into a predictive science. After it is measured, our hope is that the internal entropy decrease and the external entropy increase are two other interfunctions in the mechanisms of self-organization, development, and evolution, which means that both of them will change exponentially in time, and will be in a power law relationship between them and with all other interfunctions.

We hope that our approach will introduce a common language and theoretical framework for all systems that exhibit self-organization. The range of organized complex systems spans from nuclear systems in stars to chemical, biological, social, and economic systems. The common features of all of them are that they are out of equilibrium, that they have sources and sinks of energy, and that they become more action efficient in time, i.e., more organized. In this sequence, biological evolution is one segment in the universal definition of evolution, and possesses the same attributes as the others. We hope that using a fundamental principle built on energy and time, such as the Principle of Least Action, will unify the language for organization and evolution not only in biology but across all disciplines.

References

Annila A, Salthe S (2010) Physical foundations of evolutionary theory. J Nonequilb Thermodyn 35:301–321

Barabási A, Dezső Z, Ravasz E, Yook S, Oltvai Z (2003) Scale-free and hierarchical structures in complex networks. AIP Conference Proceedings, vol 661. pp 1–16. doi:http://dx.doi.org/10.1063/1.1571285

Bejan A, Zane JP (2012) Design in nature. Doubleday, Toronto

Chaisson EJ (2001) Cosmic evolution: the rise of complexity in nature. Harvard University Press, Cambridge

Chaisson EJ (2011) Energy rate density. II. Probing further a new complexity metric. Complexity 17:44–63

Chatterjee A (2015) Thermodynamics of action and organization in a system. Complexity. doi:10.1002/cplx.21744

de Maupertuis P (1750). Essai de cosmologie

Georgiev G, Georgiev I (2002) The least action and the metric of an organized system. Open Syst Inf Dyn 9:371–380

Georgiev GY, Henry K, Bates T, Gombos E, Casey A, Daly M, Vinod A, Lee H (2015) Mechanism of organization increase in complex systems. Complexity 21:18–28

Georgiev G, Gombos E, Bates T, Henry K, Casey A, Daly M (2016) Free energy rate density and self-organization in complex systems, Ch. 27. In: De Pellegrini S, Caldarelli G, Merelli E (eds) Proceedings of ECCS 2014: European Conference on Complex Systems. pp 321–327. Springer Proceedings in Complexity. Springer International Publishing. ISBN 3319292269

Heylighen F (1999) The growth of structural and functional complexity during evolution. In: Heylighen F, Bollen J, Riegler A (eds) The evolution of complexity. Kluwer, Dordrecht, pp 17–44

Jagers op Akkerhuis GAJM (2008) Analysing hierarchy in the organization of biological and physical systems. Biol Rev 83:1–12

Jagers op Akkerhuis GAJM (2012) Contributions of the operator hierarchy to the field of biologically driven mathematics and computation. In: Simeonov PL, Smith LS, Ehresmann AC (eds) Integral biomathics. Tracing the road to reality. Springer, New York, pp 181–190

Kauffman SA (1993) The origins of order: self-organisation and selection in evolution. Oxford University Press, Oxford, 709 pp

Lucia U (2015) Probability, ergodicity, irreversibility and dynamical systems. Proc R Soc A 464B:1089–1104

Ville R, Kaila I, Annila A (2008) Natural selection for least action. Proc R Soc 464:3055–3070

Part II
Discussion, Reflections, and Conclusions

Chapter 16
General Discussion

Gerard A.J.M. Jagers op Akkerhuis

> *"Science is a vast fiduciary system. Scientists know what they do by finding trustworthy sources and then trusting them. It is also what Polanyi called a polycentric system, in which autonomous and only loosely coordinated groups of specialists—mildly sceptical and mainly trusting—periodically keep an eye out for what is going on next door. The coherence and integrity of the body of scientific knowledge arise through these processes of mutual adjustment. Finally the bases of scientific judgment cannot be completely articulated because the 'tacit' dimension is ineliminable. It is not a fly in the formal ointment; it is what makes science science. You would understand that, Polanyi suggested, if you knew what it was like to be 'confronted with the anxious dilemma of a live scientific issue. The further away ywou are from the quotidian life of scientific practice, the more you tend to be infatuated with myths of method." (Michael Polanyi's idea of "tacit knowledge" as espoused by Steven Shapin in The London Review of Books, 15th December 2011: Polanyi, M. 1962. Personal knowledge: Towards a post-critical philosophy. Psychology Press)*

Abstract The general discussion focuses on some aspects that are of overarching relevance for all the preceding chapters. The first subject that is discussed is the relationship between systems theory and the philosophy of science. After a short summary of the principles of system science and the philosophy of science, the criteria are discussed that a ranking must meet in order to be viewed as a scientific ranking. The second subject concerns the relationship between the objects-based graph-pattern of Darwinian evolution and the extended evolutionary synthesis. Thirdly, attention is paid to the question of how to deal with the new terminology about patterns of Darwinian evolution, compared to the classical terminology about evolution as a process. It is proposed that the concept of generational morphing could be used as an alternative term for the use of evolution as a process. The discussion of these general subjects serves as a stepping stone towards the detailed discussions (in Chap. 18) of the points that are raised by our reviewers.

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_16

16.1 Relationships Between System Theory and Philosophy of Science

Any scientific inquiry about the functioning of systems is linked to two major philosophical questions. The first question is about which methods are well suited for the analysis of systems. The second question is about the criteria for scientific inquiry. Many biologists, physicists, chemists, sociologists etc. are mainly interested in the first question. Meanwhile, philosophers in particular have focused on the second question. This simple sketch arguably offers a caricature, a black-and-white picture. Yet the caricature hints at two follow-up questions. The first question is whether or not the approaches used by system scientists are scientific in the eyes of philosophers of science. The second question is whether the philosophies of philosophers can be viewed as representing good system theory in the eyes of the system scientists. Even though the second question is relevant as well, because it hints at the question of how much technical knowledge a philosopher needs to be able to critically analyse the work of a system scientist, the following text focuses on the question of whether the approaches of system scientists are scientific. Before discussing this topic, a short historical overview is offered of developments in the philosophy of science and in system theory.

16.1.1 Philosophy of Science

The thinking about how one can acquire knowledge about the world has a long history. When writing the below summary, the book of Brysbaert and Rastle (2009) served as inspiration. Early ideas expressed by Plato suggested that the soul when it entered the body brought with it innate knowledge. Later Aristotle assumed that knowledge was learned, and made a distinction between inductive reasoning and deductive reasoning. In the case of inductive reasoning rules are derived from series of observations. As there is always the possibility of a "black swan", conclusions reached through inductive reasoning are not necessarily one 100 % true. In the case of deductive reasoning, combinations of established rules are combined to new rules. The combined rule is correct if the basic rules are correct and if consistent logic is applied.

The inductive method became the basis for empiricism (Bacon) in which general rules are inductively derived from measurements and experiments. The empiricist mind-set can be recognised for example in the following statement of DiRienzo and Montiglio (2015): "We argue that conceptual papers presenting a novel hypothesis probably could almost always be replaced by robust empirical studies actually testing the hypothesis of interest." Around 1922 the so-called logical positivists of the Wiener Kreis started looking for criteria that could distinguish activities that were scientific, from those that were non-scientific. They promoted that empirical verification was the basis of the scientific method and that scientific activities had to follow a cycle of observation, induction and verification. Soon however questions emerged about non-observables, such as the variable named acceleration in Newton's theories, which could be observed indirectly only. And it was discussed that theory may also guide observations.

Popper now suggested that it would be logically impossible to test the truth of a theory that is based on observations. The reason for this was that one can never test all possible events, and that for this reason there can always be a black swan, as was indicated above as part of the discussion of inductive reasoning. To solve such problems, it was suggested that scientific ideas should in principle be phrased in such a way that they could be falsified experimentally. Based on this reasoning, Popper introduced the hypothetico-deductive method which included the following sequence of activities: observation, interpretation, hypothesis, testing. This method combines inductive and deductive reasoning. The testing should involve new observations aiming at the falsification of the theory. Falsifiability thus became an important hallmark of scientific reasoning. Later Popper added that one did not need to discard an entire theory if a prediction was wrong. Instead it may be more productive to examine whether and how the theoretical framework could be improved. *With his work, Popper links closely to the work of Newton (1687) who stated that: "In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypothesis that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions. (Newton, (1726, Rule 4)." This quote of Newton includes experiment, induction and falsification.*

A next development was Kühn's (1962) "The structure of scientific revolutions". In his book Kühn indicated that scientific progress is based on a succession of paradigms. A paradigm is a set of common views about which subjects are studied by a discipline and how this is done. Well-known paradigms in physics are e.g. the aether paradigm, the Newtonian paradigm, the paradigm of general relativity, and the paradigm of quantum mechanics. Important paradigms in biology are e.g. the paradigm of spontaneous generation, the paradigm of vitalism, or of the cell theory. Researchers generally have a strong tendency to remain focused on a dominant paradigm. Accordingly, Kühn suggested that scientific progress involves a series of phases, from normal science, to crisis, to revolution, then back to new normal science, to a new crisis, etc. *These phases show a link with Kant's (1781) syllogism of "thesis and antithesis" and the aspect of "synthesis" that was added by Fichte (1794).*

In most of the above reasoning certain realism was assumed, implying that human knowledge can be true in the sense that it mirrors in a passive way aspect of a physical reality that exists independently of human observations. This realist viewpoint was opposed by the idealist viewpoint of postmodern thinking. Postmodern philosophers suggested that scientific knowledge, as a social construction, is a subjective construction that depends on the language and culture of the scientists involved. From their point of view social constructivists assume that scientific statements represent no truth in themselves, but that such truth depends on how well a statement fits with the paradigm shared by the group.

Such claims have evoked fierce discussions, known as the science wars, between scientists and post-modern philosophers. A mid-ground viewpoint that respects both the social component of theory and the independent existence of the physical world was offered for example by critical realism, a philosophical perspective that was discussed in the introduction of this book, and by pragmatism, which goes back to Peirce (1878). Pragmatism holds an open view on knowledge, and accepts that in addition to the scientific method also other way of gathering knowledge exist, notably: (1) Tenacy, based on customs, (2) Authority, based on the opinion of agents that have acquired a certain authority, such as religious leaders and (3) *A priori* knowledge, based on how people themselves arrive at opinions, including various pathways, ranging from critical analysis to just having a hunch.

16.1.2 Systems Theory

System scientists acquire knowledge about a system as a means to improve their understanding of the system's structural and dynamic properties.

Knowledge about a system can be based on observations, measurements and experiments. In addition more insight can be gained by modelling and simulation studies. While different measurements of a system always increase our knowledge about the system, a broader theoretical context is needed if one aims at integrating such results and if one aims at translating the insights about one particular system to other systems. For this reason system scientists have not only focussed on measurements, but have additionally developed philosophical approaches for the identification and classification of kinds of systems, objects, parts and properties. The broad field of systems theory can thus be thought of as consisting of two major fields of theoretic development, one focusing on dynamics and predictions, and the other focusing on patterns and classification.

A major line of reasoning in systems research deals with the dynamics of large scale systems that consist of many interacting objects. Examples of discoveries in this field include for example the theory of self-organised criticality (Bak 1996), the Big Bang theory (Pagels 1985), the theory about tipping points (Holling 1973; Scheffer 2009), the constructal law (Bejan 1997, 2016), the identification of fractal dynamics (Lorenz 1963; Briggs 1991), the existence of power laws (Newman 2005), Moore's law (Moore 1965) and the evolution theory (Darwin 1876; Spencer 1891; Darwin and Wallace 1858).

A second line of theoretic development has focused on the identification and classification of all the different kinds of objects. These objects are viewed as the basis for analyses of how such objects through their interactions constitute large dynamic systems, or how such objects internally consist of smaller objects. Fundamental philosophical challenges in this field of research have been the definition of a system, the definition of an object, and the identification of criteria for hierarchical aspects of organisation.

The quest for defining what a system is can be viewed as a major philosophical endeavour. As discussed in Sect. 2.2.3, an early pioneer of systems theory, Bernard (1865), suggested that “les systèmes ne sont pas dans la nature mais dans l’ésprit des hommes”, indicating that humans use their conceptual powers to view a selection of objects and a selection of relationships in an integrated way as a system. More recently, Checkland and Scholes (1990, p 22) explained the conceptual nature of a system in their book about soft systems methodology, stating that it is “perfectly legitimate for an investigator to say ‘I will treat education provision as if it were a system’, but that is very different from declaring that it is a system. This may seem a pedantic point, but it is an error which has dogged system thinking and causes much confusion in the systems literature”. Checkland and Scholes (1990) called their approach soft systems methodology because the process of enquiry itself can also be analysed in a systemic way, so to speak as a “soft” system. The operator theory has added to the concept of a system that what is perceived as a system and what is perceived as an object both depend on a person’s intentions. Depending on what intensions a person has, the same object can be viewed as a system at one moment or as an object at another moment, much in the same way as a well-known picture that can look like a vase, or as two opposing faces.

Regardless of whether an entity is viewed as a system or as an object, a decision has to be taken about the spatial limit. For the identification of spatial limits one can narrow down the options by using increasingly stringent criteria.

The most general approach is to accept as an object/system any entity that can be endowed a conceptual limit. Accordingly, a selection of objects can include many things, including an individual mussel, a group of attached mussels, a cow and a herd of cows. The selection can be restricted by demanding a combination of a conceptual and a physical limit. Now one can no longer include the herd. The mussel, the group of attached mussels and the cow remain in the selection. Not every study in systems theory has taken physical attachment into account when focusing on objects. As discussed in Chaps. 8 and 10 the Major Evolutionary Transitions approach of Maynard Smith and Szathmáry (1995) focuses on cooperation, competition reduction, and reproduction as part of a larger unit. These criteria allow one to include the individual mussel, the cow and those groups in which cooperation and competition reduction take place. Most likely, a group of attached mussels has to be excluded because it is not clear whether it has always cooperation and/or competition reduction. Finally, as has been explained in Chap. 2, the Operator Theory introduces a new combination of criteria based on dual closure; a closure that is based on structural and functional criteria (see Sect. 2.5.3). Using the Operator Theory, the list of objects reduces to the mussel and the cow. Any object that meets the criteria of the Operator Theory is called an operator.

With the use of dual closure, the Operator Theory introduces a new paradigm for thinking about countable objects, individuals, holons, tokens, things, entities etc. What the Operator Theory suggests is that instead of a single hierarchy for objects, it is more appropriate to distinguish between three hierarchies. Firstly, one can identify a hierarchy of operators that have increasingly complex organisation. Secondly, one can analyse the organisation inside an operator. Thirdly, one can analyse the organisation of systems that while they consist of interacting operators are not operators themselves. Systems of interacting operators, the so-called interaction systems, can either take the form of compound objects, such as the attached mussels, or of groups, such as herds. Importantly, any analysis of organisation inside an operator or of an interaction system changes when another perspective is selected, as indicated by the DICE concept (Sect. 2.7.3).

Inspired by the work of Turchin (1977) and Heylighen (1989), the Operator Theory introduces the concept of dual closure as a yardstick for the distance between subsequent levels in a hierarchy of increasingly complex operators. Classical approaches generally either lacked clear criteria for a next level, or criteria were suggested that referred to quantitative measures, such as the powers of ten approach. A drawback of quantitative measures such as "powers of ten" is that they do not account for qualitative aspects of organisation. For example, it one aims at distinguishing between a unicellular organism such as a protozoon, and a multicellular organism such as a plant, it is meaningless to suggest that a plant must be ten times bigger than a protozoon. Firstly, a plant can be anything in between of two times and several million times larger than a single cell. Secondly, size is not the reason why a multicellular organism is called a multicellular organism. What this example demonstrates, is that for qualitative differences one needs qualitative criteria.

16.1.3 The Importance of Rankings for the Scientific Method

The above shows that in system science, the concepts of hierarchy and ranking play and important role. Because of this popularity, it is a relevant question whether or not rankings can be viewed as tools that accord with the scientific method.

To find out about whether or not rankings are scientific tools, this section starts with a broad view on the scientific method, while using Popper's hypothetico-deductive method as a basis. The scientific method focuses on the improvement of theoretical constructs, such as descriptions, models, definitions and classifications. The development of such constructs can involve different methods (e.g. inductive, deductive) and is part of a culturally and technologically supported process. Constructs are embedded in a broader theoretical context, called a paradigm. To comply with the scientific method, it should be possible to in principle perform tests that can falsify a theoretical construct. If a construct's logic fails a test, the construct should be improved or rejected. The better a construct can be underpinned and tested and the wider the application of the construct, the greater the scientific relevancy of the construct will be.

If a ranking is viewed as a theoretical construct, the scientific method can be used to test a ranking. Basically a ranking consists of classes of objects, while the objects in the different classes are connected by some kind of relationship. If objects in different classes of a ranking have no relationship, this situation will be viewed as a non-ranking. A non-ranking has unique and unrelated rules for the objects in every class. A non-ranking cannot be used for predictions, because the objects in one class offer no information about objects in any other class. For example in the kitchen one can have glass jars with spices. In principle the knowledge that there is pepper in one jar, and cinnamon in another, offers no information about what spice will be in any next jar, unless the jars had been placed in some order. This implies that if one aims at using a ranking as a basis for a prediction, a ranking must have some kind of regularity, while only rankings that have regularity can result in specific predictions that can be tested using the scientific method.

In relation to a focus on regular rankings and their use for creating predictions, it is interesting to bring back to mind Ockham's razor and related criteria that are discussed in Sect. 1.4. We refer to Ockham's razor because a comparison of any two rankings will generally allow the identification of one ranking with equal power but fewer rules, or one ranking that includes fewer ambiguous concepts. Thus, while the scientific method is based on predictions, part of the testing of a ranking can already start in an earlier phase. In this phase an existing ranking can be compared with a real or a hypothetical alternative. Such a comparison can focus on several logical aspects:

1. Every concept that is included in a ranking can be checked for ambiguity. Such a check can ask the question of whether or not the concept that is used is defined in a clear way. If a definition is ambiguous, this may cause confusion about which objects are referred to, or whether or not an object belongs to a specific class in the ranking.
2. For successive classes in a ranking it can be checked whether there is a consistent use of kinds of concepts. Entities in successive classes in a ranking have to be of related kinds.
3. It can be checked whether the rules that are used for creating the ranking are unambiguous. Like concepts, also the ranking rules need proper definitions to prevent ambiguity.
4. A ranking rule can fit to a part of the ranking, or to the entire ranking. If the same ranking rule can be used to connect more than two classes, this speaks in favour of the simplicity of the ranking.

If of any pair of rankings, one performs less well with respect to one or more of the above criteria, this ranking will be less suitable for creating precise predictions. By analogy, any ranking that achieves the same results with a lower number of rules will be favoured by Ockham's razor.

Finally, it is relevant to remark that discussions about whether or not a classification is scientific, have a different goal than discussions about the utility of a classification. The utility of a classification and other theoretical constructs depends on the kind of context one has in mind for their use.

16.1.4 Testing Existing Classifications with the Help of Ockham's Razor

In the preceding paragraph it is suggested that Ockham's razor can be used as a check of the simplicity of a ranking and the clarity of its classes and concepts. For example, if one and the same ranking includes both steps between classes with objects, and steps between classes with groups, this suggests that the ranking is based on two or more ranking rules. And if a ranking includes objects in one or more classes that are defined ambiguously, the use of Ockham's razor suggests that the logic of the ranking can be improved. At the same time, arbitrary class limits cannot be avoided when subdividing a continuous variable, such as when a continuum of wavelengths of light is split into the colours of the rainbow (see Sect. 1.3.3).

In the following examples Ockham's razor is used for suggesting improvements of several classical rankings that one after the other can be viewed as innovative steps in the ongoing exploration of how a hierarchical approach can assist in an analysis of nature's complex organisation.

16.1.5 Young

The first ranking that is examined is that of Young (1976). Young arranges a number of classes, called kingdoms, and discusses properties that belong to the entities in the classes (Table 16.1).

Ockham's razor can be applied for examining the ranking of Young based on seven kingdoms (Table 16.1). For example, to explain the step from the atomic kingdom to the molecular kingdom, one would need a construction rule that indicates how the small entities in the atomic kingdom integrate to form the larger entities in the molecular kingdom. A construction rule that explains the step from atoms to molecules, however, would not consistently fit in with the other steps in the ranking. For example, if by analogy with the step from atoms to molecules, one would view molecules as the building blocks of the cell, the next kingdom should typically include cells. However, the next kingdom is the vegetable kingdom. This kingdom includes both unicellular and multicellular organisms. At the same time, multicellular organisms can be viewed as a next step, because they are constructed from single cells. This demonstrates that the ranking uses different rules for the inclusion

Table 16.1 "The grid" of Young (1976, pp 86–87)

Kingdom	Examples
1. Light (potential)	From cosmic high energy rays to low frequency waves
2. Nuclear (binding)	Not given
3. Atomic (identity)	Different selections from the periodical table
4. Molecular (combination)	Metals, salts, methane series, functional compounds, polymers, proteins, DNA/viruses
5. Vegetable (growth)	Bacteria, filamentous algae, bryophytes, psilophytales, Calamites, gymnosperms, angiosperms
6. Animal (mobility)	Protozoa, sponges, coelenterates, mollusks, annelids, arthropods, chordata
7. Dominion (consciousness)	Tribal societies, modern man, Christ/Buddha

of objects in the molecular kingdom than are used for the includions of objects in the vegetable kingdom.

As another check, one can also focus on the ontological kinds of the entities that a kingdom refers to. If one looks at the atomic kingdom and the molecular kingdom, each of these kingdoms refers to objects that inside their class are all of a uniform kind, because every object involved either represents an atom, or represents a molecule. If one now looks at the classification of an entity as a plant or as an animal this focuses on a different parameter than was used before. When distinguishing between plants and animals one zooms in on the kinds of endosymbionts that live inside the cells of the organisms. In animal cells one selectively finds mitochondria, whilst in plant cells one finds mitochondria as well as chloroplasts.

Apparently, the ranking makes use of different rules for steps towards next classes. A final example of differences in ranking rules and kinds of entities discussed here is the inclusion of tribal societies in the kingdom called dominion. Tribal societies represent entities of the kind “group”, and the inclusion in the ranking of a concept such as a group causes a break with the rankings logic so far, because all lower classes in the ranking included entities of the kind “material object”, while all the higher levels refer to entities of the kind “group”.

16.1.6 Miller

Miller (1985) suggests a theory that is quite similar to that of Young (1976). The approach is explained by Miller in the following citation:

“Seven levels of living systems can be identified, each with characteristic structure and processes, and each composed of system at the level below. The seven levels are: cell, organ, organism, group, organisation, society, and supranational system. The structure, that is, the arrangement of their components in space, and the functional and historical processes of systems at each level are characteristically different from other levels, although the levels grade into each other in such a way that some systems may be difficult to classify. With some exceptions, systems at each higher level are larger than those lower in the hierarchy.” (Miller JG 1985).

Table 16.2 Levels of living systems according to Miller (1985)

Levels used in living systems theory
1. Cell
2. Organ
3. Organism
4. Group
5. Organisation
6. Society
7. Supranational system

We can now analyse the ranking of Miller (1985) in the same way as the ranking of Young (1976). First, it can be deduced from Miller's ranking (Table 16.2) that the cell and the organ are viewed as levels of organisation that reside inside a multicellular organism. When looking at the ranking this way Miller uses the concept of the organism as referring selectively to a multicellular organism, even though the concept may refer to several specific kinds of organism, such as unicellular organisms, or multicellular organisms, or may in a general way refer to all entities that are viewed as organisms. This implies that the concept of the organism can be interpreted in different ways, which causes ambiguity.

The use of objects inside an organism, such as cells and organs, and the use of the concept of the organism, which can mean different things, demonstrates that the concepts that are ranked are not all of the same kind. If the analysis is extended to the next steps in the ranking, these are: group, organisation, society, and supranational system. While these are all different groupings of interacting organisms, one can observe that such groupings again represent different ontological kinds than cells, organs and organisms. The mixing of ontologically different kinds of entities in a single ranking implies that the ranking cannot consistently be based on a single kind of rule. Miller also remarks that "… the levels grade into each other in such a way that some systems may be difficult to classify." According to Ockham's razor a confession about inherent ambiguity indicates that there is room for improvement.

16.1.7 Stikker

Stikker (1992) offers an interpretation of the cosmogenesis that Teilhard de Chardin describes in his book "The phenomenon of man" (1940, published in 1955). The idea is that "… in the history of the universe, new phenomena emerge in a continuous process of increasing complexity, culminating at present in the most complex and most unified phenomenon of organisms: the human being" (Stikker 1992, p 52). The interpretation of Stikker seems to be inspired by Young (1976). Like Young (1976), Stikker (1992) suggests a range of classes, while in every class the objects can range from simple to complex. In addition to Young (1976) the limits of the classes in Stikker's approach are more tightly coupled to transitions of a specific kind, and the vegetable kingdom and the animal kingdom of Young (1976) are replaced by the concepts of the cell and the organism. Such changes lead to improvements of the consistency of the reasoning and improve the clarity about the kinds of entities that can be found in the classes.

As a test for consistency of the ranking, one can focus on the construction-relationships between the levels. For example several atoms can integrate to form a molecule. And several molecules can integrate for form a cell. As a next step several cells can integrate to form an organism. The differences between the entities in subsequent boxes are caused by a transformation, a discontinuity, a leap or a one-time event.

The ranking of Table 16.3 still uses a mixture of rules for the distinction of next levels. Like in the work of Miller (1985) it seems as if the concept of the organism

Table 16.3 The diagram of levels in evolution according to Stikker (1992)

Transition and level	Small form	Large forms
1. Void/radiation to matter	Hydrogen	Californium
2. Atom to molecule	H_2	DNA
3. Molecule to cell	Prokaryotic cell, virus	Bacteria
4. Cell to organism	Eukaryotic cell	Man
5. Organism to cooperation (a whole of organisms)	Beehive	Humanity
6. Cooperation to global mind (a complex whole of cooperations)		

is used selectively as a reference to a multicellular organism. Meanwhile, the cell in the scheme of Stikker seems to refer to an autonomously dwelling entity that classifies as a unicellular organism. And just like Young (1976) and Miller (1985), Stikker (1992) adds groups of different kinds to the top of the ranking. With the inclusion of groups, the overall approach ranks entities of different kinds, both material objects and groups, indicating that the ranking is not uniform. Finally, a virus is grouped together with small cells without a clear explanation being offered of what is meant with a virus or why a virus is grouped together with cells.

16.1.8 In Conclusion

Above a range of classifications is discussed with similar goals as the Operator Hierarchy. Attention is paid to the consistency of the criteria that are used for creating the rankings. The results suggest that a check of the consistency of the criteria can indicate whether a classification complies with the scientific method. The results also demonstrated that logical checks do not require predictions. Instead, one can check for the use of similar ontological kinds in a ranking. Or one can check the consistency of the application of ranking rules.

These results also indicate that the concept of internal consistency can be used as a criterion for testing whether or not the Operator Hierarchy is a scientific classification. In this sense, the Operator Hierarchy can be viewed as a falsifiable theoretical construct. An analysis of the internal consistency of the ranking rules and kinds of object of the Operator Hierarchy can be found in Chap. 2.

16.2 Relationships with the Extended Evolutionary Synthesis

This section focuses on different representations of the extended evolutionary synthesis.

16.2.1 The Extended Evolutionary Synthesis

The standard view of the modern synthesis has been challenged by researchers such as Stebbins and Ayala (1981), Pigliucci (2007), Depew and Weber (2013), Jablonka and Lamb (2005, 2014) and Laland et al. (2014). These authors have suggested that evolutionary theory in biology has constrained evolutionary thinking, because it has become too strictly focused on genetics. It was claimed that evolutionary thinking may benefit from supplementing the genetic basis with a range of insights that have been developed in biology-related disciplines, including developmental biology, genomics, the evolution of evolvability, epigenetics, phenotypic plasticity and learning.

To allow the inclusion of novel insights a “rethink” has been suggested that should lead to an “Extended Evolutionary Synthesis” (Pigliucci 2007). A claim of the extended synthesis is that the standard evolutionary theory (SET) “largely retains the same assumptions as the original modern synthesis, which continues to channel how people think about evolution” (Laland et al. 2014). For example, an Extended Evolutionary Synthesis must account for:

1. Physical rules of construction (e.g. a segmented body) affecting the possibilities for the gene-based (allele-based) generation of variety.
2. The effect of the environment on development (via phenotypic plasticity).
3. The impact organisms have on their environment (niche construction) and the feedback resulting from this.
4. The transfer of more than DNA to the next generation (e.g. epigenetics and hormonal information).

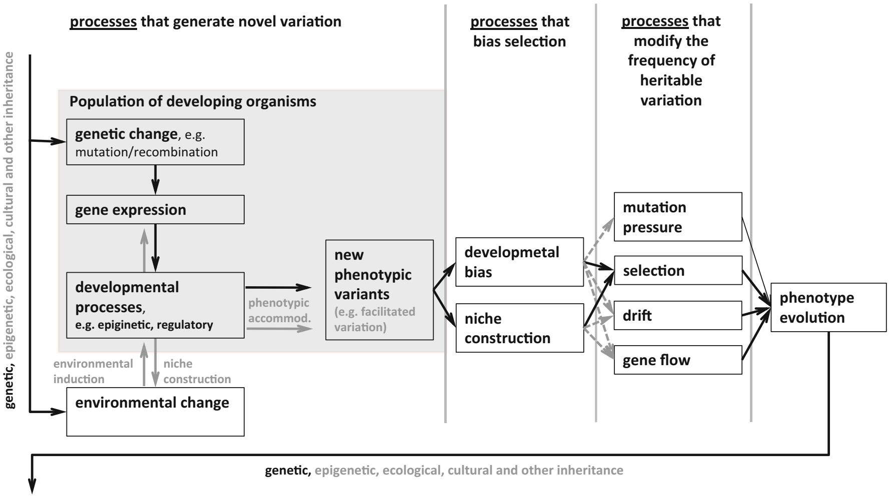

Fig. 16.1 The structure of the Extended Evolutionary Synthesis with a focus on the processes involved (Modified after Laland et al. 2015. Proc R Soc Lond B)

In a recent study, Laland et al. (2015, Fig. 2) suggested a graphical overview of the structure of the extended evolutionary synthesis (see Fig. 16.1). The overview is presented in the form of a flow-diagram that starts with processes that generate novel variation, followed by processes that bias selection, processes that modify the frequency of heritable variation, and the process of phenotype evolution.

Figure 16.1 indicates that the extended evolutionary synthesis focuses strongly on the processes that contribute in different ways to the emergence of the pattern of Darwinian evolution. From the current perspective, and as already indicated in Sect. 4.3.5, such a focus can be viewed as a relevant development that redirects the attention from gene fractions in populations, to explanatory processes. Now that the extended synthesis adds many new aspects, a structured organisation of all these aspects becomes an important asset.

In this context, it is relevant to examine the flow chart of Fig. 16.1. The organisation of this flow chart suggests that events happen in a logical order. For example, one starts with the processes that generate novel variation, and continues with niche construction and development (which are different kinds of concepts), after which selection and drift occur etc. At least some of these processes, notably those that involve feedback, can also be viewed as occurring simultaneously. The scheme focuses on processes that involve whole organisms, or that occur inside organisms. However, the organisms themselves are not explicitly included in the scheme. And one can also observe that Fig. 16.1 uses selection in the classical interpretation, namely as a process, instead of as the pattern discussed in this book. As will be demonstrated in the following paragraph, the application of the perspective of the object-based graph-pattern for Darwinian evolution can be used as a basis for a new chart that includes individual organisms, that can deal with simultaneously occurring processes, and that refers to variation and selection as evaluative patterns.

16.2.2 Using a Graph-Pattern for Organising Factors that Lead to Darwinian Evolution

As a contribution to the goal of organising the processes that cause Darwinian evolution, the following text suggests how the factors included in the flow chart of Laland et al. (2015) can be organised with the help of an object-based graph-pattern for Darwinian evolution. While aiming at demonstrating the contribution of the graph-pattern of Darwinian evolution, two different patterns will be discussed:

1. A biological extension. This extension focuses on the pattern for sexually reproducing multicellular organisms, and includes a developmental history that starts with an egg cell, and that proceeds towards an adult stage that starts with an egg cell, and that proceeds towards has a complex neural network. This example retains a close link with the extended evolutionary synthesis because it focuses on organisms.

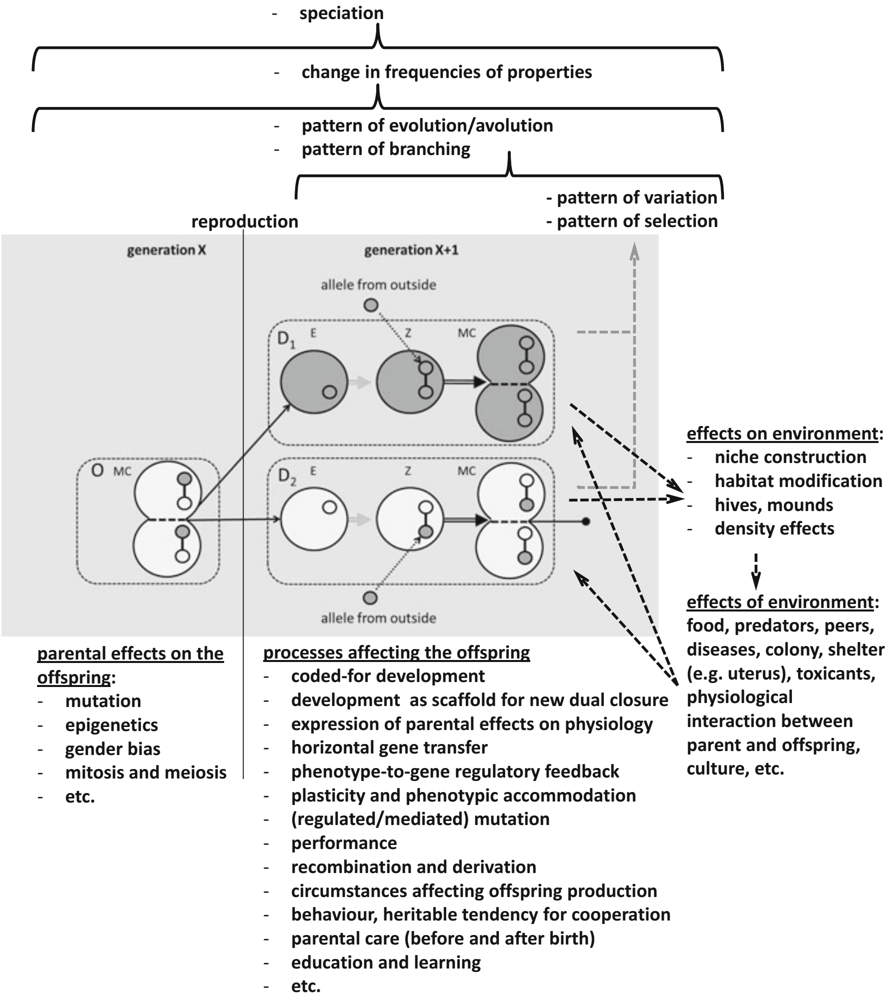

Fig. 16.2 Using an object-based graph-pattern as a basis for organising the concepts involved in the extended evolutionary synthesis. The graph is based on a sexual multicellular species with a neural network. *E* ovum, *Z* zygote, *MC* multicellular stage, which is assumed to have a neural network and can learn. *Boxes* surrounded by *dashed grey lines* represent developmental histories. *Dashed black arrows* indicate effects. A *line with a dot* symbolises reproduction leading to an offspring. Even though this is not indicated in the graph, the environment and the parental organism also mutually affect each other

2. Generalising the extended pattern. Now the focus is on a generalisation of the pattern of Darwinian evolution at the smallest scale to include any kind of objects that comply with the criteria of the pattern, regardless whether these are organisms or not. This generalisation will make use of the general terminology that was introduced in Chaps. 4 and 6.

A Biological Extension

In the biological example of an extended theory (Fig. 16.2), the object-based graph-pattern of Darwinian evolution is filled in for a sexually reproducing multicellular organism that in its adult stage has a neural network. Figure 16.2 is based on a single parent who produces two offspring, while the developmental history of both these offspring includes the ovum, the zygote and the multicellular stage with a neural network. The concepts that are discussed by the extended evolutionary synthesis are listed at the sides of the graph. These concepts are divided into four groups.

The first group includes the concepts that refer to the relationship between the mother organism and her offspring. The focus is on processes that occur in advance of the moment that the offspring meets the criteria of representing a separate operator. After that moment, effects of the parent are viewed as special interactions with the environment of the offspring. Processes that accord with this viewpoint are: mutation, epigenetics, gender bias and mitosis, and meiosis. These are all processes in which the parent determines the properties of the offspring.

The second group of processes involves parameters that affect the lives of the offspring. In some of these processes the origin lays within the organism, for example a mutation in the DNA may cause cancer, or epigenetic coding by the parent may alter the expression of genes in an offspring. Another factor that largely works from within is the effect of gene regulation during the development from a zygote to a newborn offspring, and later during the development from a juvenile to an adult. In addition there are regulatory feedbacks between phenotype and gene regulation. Furthermore, an organism can involve in horizontal gene transfer, or when its brains allow this, exchange information with peer organisms. The changes in the organisms can also be mediated by external influences. For example, the mutation rate in the organism can be altered as a consequence of external clues. And when alleles are obtained from other organisms (e.g. semen) the local abundance of peer organisms with certain alleles has a major influence on the chance of receiving a specific allele. Here one can also focus on the property that an organism may experience a desire to live close to other similar organisms, in groups, herds etc. And, lastly, but importantly, and as discussed in Chap. 6, the developmental history may also scaffold the realisation of new dual closures. An example of the latter is the transition from unicellular to multicellular organisation and from multicellular organisation to organisms with neural networks.

Thirdly, in an object-based approach it is easy to include, as an ongoing process, the effects that organisms can have on their environment. Especially when organisms are not very mobile, effects of their normal living activities, such as grazing, behavioural competition, burrowing and the pulling over of trees can have a strong effect on the local environment. Here one can both think of passive influences on the environment, such as depletion of food, or of active effects that increase the chances of survival. Active effects not only include for example beaver dams but also include cultural phenomena such as agriculture and the building of cities. A somewhat futuristic change in the living environment of humans that may occur in the near future is the introduction of artificially intelligent, autonomously acting agents.

Fourthly, when organisms change their environment, they have to deal with the changed conditions. Aspects of the environment that can easily be overlooked, but may have a large influence, are the density dependent interactions with peer organisms.

Generalising the Extended Pattern of Darwinian evolution

Above it was explored how the processes of the extended evolutionary synthesis could be linked to the object-based graph-pattern of Darwinian evolution. The example was based on multicellular sexual organisms. The example focusing on organisms, however, the results were relevant for an extended approach to biology oriented versions of Darwinian evolution, but could not yet be used as a general approach.

The aim of this book, however, is not to discuss a generalisation inside biology, but to formulate a more general goal, aiming at the construction of a generalised approach to Darwinian evolution. Such a generalisation should in principle be applicable to any object, organisms and non-organisms alike, assuming that such objects comply with the criteria for derivation, variation and selection that are discussed in Chap. 4 and the generalisations in Chap. 6.

A basic sketch of a general extension of the pattern of Darwinian evolution is offered in Fig. 16.3. This extension is general in the same way as the graph-pattern of Darwinian evolution at the smallest scale is general. The sketch represents a basic mould that in its current form, or after elaborations, can be used to check whether or not any existing situation fits in with the family of patterns that are all of the Darwinian evolutionary kind.

In Fig. 16.3 one can again recognise the same four groups of relationships that are discussed in the previous example. However, this time, the focus is not on organisms and offspring, but on objects and derived objects. These properties of the four groups can now be described as follows:

1. Influences that the original object can exerts on the derived objects.
2. Influences that the derived objects undergo from within or from outside and that affect their dynamics. These influences may increase or decrease the persistence of the objects, and the probability that they realise derivation.
3. Influences that the original and the derived objects may exert on their environment.
4. Influences that the environment may exert on the original and derived objects.

In addition to these four groups of causal factors, Fig. 16.3 also includes the evaluations of specific kinds of differences, such as variation and selection, and evaluations of specific kinds of overall patterns, such as evolution, avolution, branching and differential branching, that are discussed in Sect. 4.5. At the top of the figure it is indicated that the classical interpretation of evolution as change that

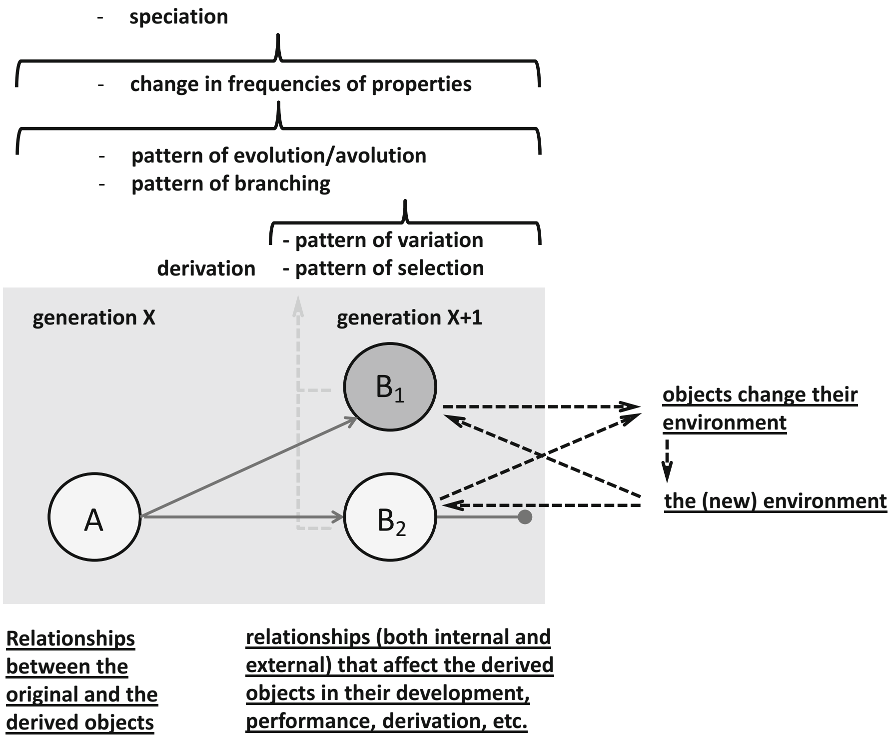

Fig. 16.3 A minimalised general and extended object-based graph-pattern for Darwinian evolution. The text accompanying the pattern introduces four groups of parameters that can be detailed for "extending" the approach. For explanation of symbols and relationships see Fig. 16.2. Even though this is not indicated, the environemnt and original can also affect each other

leads to speciation, or as change in frequencies of one or more properties of object in a group, can both be viewed as a meta-level phenomena, which integrate effects over all patterns that potentially are produced by the objects residing at the lowest level of analytic aggregation.

16.3 The Use of Terms in Evolutionary Science

In the Chaps. 4 and 6 it was indicated that the concept of evolution originates from the general Latin source "evolvere", which means "to unroll" or to "roll forward". The broad Latin conceptualisation allows one to refer to many different phenomena as being evolutionary processes, because there are many things that "roll forward" in time. However, as argued in Chap. 4, while many processes contribute to the pattern of Darwinian evolution, the pattern itself is not a process. If this result is taken seriously it would imply that the Darwinian pattern of evolution cannot be viewed as belonging to the set of processes. Accordingly, one may suggest that the universe harbours many evolutionary processes, while at the same time it is ontologically incorrect to include Darwinian evolution in the set of all these evolutionary processes. Including Darwinian evolution would be incorrect, because in the perspective of this book Darwinian evolution represents a pattern, not a process. Even if one assumes that there can be many different patterns of Darwinian evolution, the set of all these patterns cannot be viewed as a subset of a larger set of processes, simply because a pattern is not a kind of process.

The above may seem a provocative message to evolutionary scientists both inside and outside biology. Biologists may find it disturbing that "their" evolution concept, which since ages has been viewed as a process, may instead have to be viewed as a pattern. If one is used to speaking about evolution as a process, it may actually feel uneasy to alter sentences towards a pattern view of Darwinian evolution. However, as explained in Chaps. 4 and 6, there are good reasons for classifying Darwinian evolution as a pattern.

It may now be profitable for the clarity of communication in science to suggest solutions for the conflicting use of the concept of "evolution" for processes and patterns. One solution would be to stick to the Latin source "evolvere", and continue viewing the term evolution as referring to a process. Now any construction in which the term evolution is used would have to be a process is advocated in this book, however, there are good reasons for viewing Darwinian evolution as a pattern. Sticking to the Latin origin would thus imply that a new term had to be invented for Darwinian patterns. Such a decision would conflict, however, with the very general acceptance of Darwin's ideas as the paradigm case of evolution.

Another option would be to link the concept of evolution to a family of Darwinian patterns, an in this way stay close to the core of Darwin's ideas. Such a decision would create ontological clarity about (Darwinian) evolution representing a pattern. If this choice is made, however, processes could no longer be seen as representing (Darwinian) evolution.

In the context of this book, the second option seems the most appropriate. It would link the term evolution directly to the pattern of Darwinian evolution, which would imply that an alternative term must be found for processes. Such an alternative may be represented by Bejan's concept of "morphing" (Bejan 1997). Morphing describes how a flow system changes over time. Accordingly, one can use the concept of morphing to describe how solar flames are formed and how they expand into the universe. And morphing can also be used for describing the dynamics of celestial bodies in galaxies, the formation of mountains and the meandering of a river. An extension of the concept of morphing that was suggested in Sect. 14.1.5 is generational morphing, which is morphing that leads to derivation. Using generational morphing, it is possible to create a link with Darwinian evolution, because generational morphing processes can over time produce many different patterns, while some of such patterns represent the pattern of Darwinian evolution.

References

Bak P (1996) How nature works: the science of self-organised criticality. Copernicus Press, New York, NY

Bejan A (1997) Advanced engineering thermodynamics. Wiley, New York

Bejan A (2016) The physics of life. The evolution of everything. St. Martin's Press, New York

Bernard C (1865) Introduction à l'étude de la médicine expérimentale. Paris

Briggs K (1991) A precise calculation of the Feigenbaum constants. Math Comput 57:435–439

Brysbaert M, Rastle K (2009) Historical and conceptual issues in psychology. Pearson Education Limited, London

Checkland P, Scholes J (1990) Soft systems methodology in action. John Wiley & Sons Ltd. Chichester, West Sussex, England

Darwin C (1876) On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life, 6th edn. John Murray, London

Darwin C, Wallace AR (1858) On the tendency of species to form varieties; and on the perpetuation of varieties and species by natural means of selection. Zool J Linn Soc 3:46–50

Depew DJ, Weber BH (2013) Challenging Darwinism: expanding, extending, replacing. In: Heylighen F (1989) Self-organization, emergence and the architecture of complexity. Proceedings of the 1st European Conference on System Science, AFCET, Paris, pp 23–32

DiRienzo N, Montiglio P-O (2015) Four ways in which data-free papers on animal personality fail to be impactful. Front Ecol Evol 3:1–5

Fichte JG (1794) Grundlage der gesammten Wissenschaftslehre (Foundations of the entire science of knowledge). Christian Ernst Gabler, Leipzig

Heylighen F (1989) Self-organization, emergence and the architecture of complexity. In: Proceedings of the 1st European Conference on System Science (AFCET, Paris) p 23-32

Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 4:1–23

Jablonka E, Lamb MJ (2005) Evolution in four dimensions: genetic, epigenetic, behavioral, and symbolic variation in the history of life. MIT Press, Cambridge

Kant E (1781) Kritik der reinen Vernunft (Critique of Pure Reason). Hartknoch, Riga

Kühn TS (1962) The structure of scientific revolutions. University of Chicago Press, Chicago

Laland K, Uller T, Feldman M, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J, Wray GA, Hoekstra HE, Futuyma DJ, Lenski RE, Mackay TFC, Schluter D, Strassmann JE (2014) Does evolutionary theory need a rethink? Nature 514:161–164

Laland KN, Uller T, Feldman MW, Sterelny K, Müller GB, Moczek A, Jablonka E, Odling-Smee J (2015) The extended evolutionary synthesis: its structure, assumptions and predictions. Proc R Soc Biol Sci 282(1813):20151019

Lorenz EN (1963) Deterministic nonperiodic flow. J Atmos Sci 20(2):130–141

Maynard Smith J, Szathmáry E (1995) The major transitions in evolution. W.H. Freeman Spektrum, Oxford

Miller JG (1985) General living systems theory. In: Pichot P et al (eds.) Biological Psychiatry. Higher Nervous Activity. Springer Science & Business Media, New York.

Moore GE (1965) Cramming more components onto integrated circuits. Electronics. Retrieved 22 Aug 2011

Newton I (1726) Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy), 3rd edn. William & John Innys, London

Newman MEJ (2005) Power laws, Pareto distributions and Zipf's law. Contemp Phys 46:323–351

Pagels HR (1985) Perfect symmetry: the search for the beginning of time. Simon and Schuster, New York

Peirce CS (1878) How to make our ideas clear. Popular Science Monthly 12:286–302

Pigliucci M (2007) Do we need an extended evolutionary synthesis? Evolution 61:2743–2749

Scheffer M (2009) Critical transitions in nature and society. Princeton studies in complexity. Princeton University Press, Princeton, NJ

Spencer H (1891) Essays: Scientific, political, and speculative. Library Edition, vol 2. Containing Seven Essays not before republished, and various other Additions. Williams and Norgate, London

Stebbins GL, Ayala FJ (1981) Is a new evolutionary synthesis necessary? Science 213:967–971

Stikker A (1992) The transformation factor. Towards and ecological consciousness. Element, Rockport

Turchin VE (1977) The phenomenon of science, a cybernetic approach to human evolution. Colombia University Press, New York

Young AM (1976) The reflexive universe, A Merloyd Lawrence book. Delacorte, New York

Chapter 17
What Comes Next? The Operator Theory as an Operationalisation of the Teilhardian View on Cosmogenesis

Hub Zwart

Abstract The scala naturae represents the classical viewpoint that a basic tendency can be discerned in nature towards increasing complexity. This viewpoint has been vehemently challenged and loathed as romantic and unscientific by countless opponents. Yet, continental philosophers from Hegel to Sloterdijk have discussed the persistent drive towards complexity in terms of a vertical dimension of existence. In the context of discussions about the pro's and con's of hierarchical complexity rankings the Operator Theory constitutes a provocative gesture by recasting the scala naturae in a scientific form that is compatible with physics and biology. In this revised form, the idea of a scala naturae becomes partly compatible with the ideas of the French philosopher and priest Teilhard de Chardin. Teilhard de Chardin's body of work reveals a growing complexity in evolution from the geosphere and the biosphere up to the noosphere, a viewpoint which concurs in many respects with the stages and closures outlined in the Operator Hierarchy, while Teilhard's 'natural units' can be likened to the operators. However, where Teilhard de Chardin assumes that we are heading for an Omega Point, the Operator Theory rather points in the direction of technical intelligence and robotics.

17.1 The *Scala Naturae* Revisited

The *Scala naturae* concept—i.e., the idea that certain levels of complexity can be discerned in nature, and that the history of life and evolution is characterised by a basic tendency towards *increased* complexity—has been vehemently challenged and discarded as 'romantic', 'unscientific' or 'pre-scientific' by a large number of

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_17

opponents, most eloquently perhaps by Stephen Jay Gould in his book *Ontogeny and Phylogeny* (1977). The very idea of a drive towards complexity is often regarded as belonging to a metaphysical worldview, and as incompatible with a modern biological approach. Many see it as a remnant of *Naturphilosophie*, inspired by philosophers such as Hegel and Schelling and predating what Gaston Bachelard (1938) has referred to as the 'epistemological rupture', i.e., the birth of real (detached, quantitative, experimental) science. And yet, up to the present, the *Scala naturae* concept proves to be a remarkably stubborn and recurring idea, resurging every now and then as a kind of 'return of the repressed', and as a philosophical, but also as a biological conception.

Several continental philosophers (from Hegel, Schopenhauer and Nietzsche up to Binswanger and Sloterdijk) have thematised this persistent drive towards increased complexity in terms of the *vertical* dimension of existence, a dimension which is most obviously noticeable in humans. Human beings, these authors claim, not only strive for continuation, propagation and reproduction (the horizontal dimension), but also for optimisation and self-improvement (both individually and collectively), through exercise, experimentation and technology.[1] We human beings are regarded as unhappy animals par excellence, aiming to surpass and transcend ourselves, frantically trying to attain a higher level of existence. At the same time, this human tendency can be regarded as an exemplification (or intensification) of a basic drive discernible in nature as such: the so-called 'will to power' (Nietzsche), the drive to surpass and grow; the desire to experience a dramatic transformation, a leap-like change. And while Schopenhauer and Nietzsche regarded it as a blind process more or less, Hegel has argued that a certain logic or even dialectics can be discerned in it, so that we are not only able to flesh out a reconstruction of the past and a diagnostics of the present, but also a prognostics of the emerging future (what will be the next unfolding step?). One could argue, moreover, that a kind of Hegelian dialectical dynamics is even reflected in the history of the *scala naturae* idea as such. It sets off as a static vision ('thesis'), provoking an antithetical denial in modernity (i.e., the claim that there is no such thing as increased complexity in nature); but finally giving rise to a *dynamical* view of increasing complexity as the basic narrative of evolution (the 'synthesis'), for instance in the form of the operator theory.

Against the backdrop of this polemical debate between critics and adherents—which to a certain extent tended to coincide with a debate between disciplines, namely biology and (continental) philosophy—the operator hierarchy constitutes a provocative gesture. It aims to rehabilitate the *scala naturae* idea by recasting it in scientific and biological terms, in close dialogue with insights from contemporary research fields. From this perspective one could argue that the operator theory seems congruent with an important precedent, namely the view of Teilhard de Chardin, a Jesuit priest, but also a paleo-anthropologist, who contributed to the discovery of *Homo erectus* fossils in China in the 1920s and whose views were already briefly discussed above, notably because of his influence on authors such as Stikker (1992). In the next section, I will summarise his views, notably building on his book *The Phenomenon of Man*, published shortly after his death (in 1955).

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[1] See for instance Sloterdijk (2009) for a recent recapitulation of this view.

17.2 Evolution Becoming Conscious of Itself

In the history of the universe, Teilhard (1955) argues, a continuous process towards increased complexity can indeed be discerned. In the history of planet earth, as a theatre of evolution, we find this reflected in the development of a series of subsequent layers of increasing complexity: from the (abiotic) geosphere via the (living) biosphere up to the man-made noosphere (i.e., the evolving layer of intelligence and technology and their networks and products, relentlessly and increasingly absorbing and reorganising both the geosphere and biosphere). Entities of greater complexity emerge from basic building blocks (true natural units), as was already briefly explained earlier in this volume, so that radiation gives rise to atoms, atoms to molecules, molecules (via crystals and polymers)[2] to biomolecules (biopolymers) and living cells (with their 'exceptional aptitude to branch out into new forms', giving rise to a diffuse super-organism, a living film, p. 94), and from single cells to eukaryotic organisms.

Teilhard's starting point is the claim that evolution indeed displays an orientation, an axis, a line of progress, a direction, namely towards increased complexity, towards self-consciousness and self-directedness. In the laboratory of the universe, a trend towards synthesis and sublimation can be discerned. This notably applies to life, a decidedly 'experimental' form of reality (p. 77). Life is a process of synthetic sublimation which, via endless permutations and combinations of basic units, gives rise to a mega-synthesis of complex forms (p. 106). In other words, life not only propagates, but *ascends* as well (p. 107). In the course of evolution, moreover, living entities are increasingly able to consciously co-determine the conditions of their own existence. And this applies in a rather outspoken manner to the most recently evolved species, namely humans.

Teilhard sees human beings as 'evolution becoming conscious of itself' (p. 181). Evolution is basically a process of 'sublimation' (p. 106), transposing physiology into culture, culminating in a process of cerebralisation and, ultimately, of self-conscious self-directedness. In Homo sapiens, the deluge of cerebralisation gave rise to completely new forms of experimentation via technology, language, science and art. Teilhard is well aware that in mainstream biological discourse such claims are encountered with disavowal, but for Teilhard, 'sublimation' constitutes an undeniable evolutionary dynamics.

Currently, Teilhard argues, we find ourselves on the verge of a rather decisive turn. Due to global human activity, a new layer has emerged, over and above the biosphere, namely the noosphere, which literally means the 'thinking layer' (derived from the Greek term νούς: i.e., 'mind' or 'intellect') which, besides noetic activities, also involves noetic products (technologies, devices, culture, infrastructures, industrial plants, airplanes and so on). In other words, the noosphere is evolving into a planetary network of advanced technologies and global collaborative circuits. Humans are obviously animals, and yet we represent a discontinuity, a leap, a crisis,

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[2] Teilhard refers to polymerisation as an emerging `work of synthesis' (p. 70)

a metamorphosis, an awakening, giving rise to the emergence of the noosphere, the thinking layer, relentlessly transforming and absorbing the biosphere. Indeed, the noosphere represents a conscious reshaping of the world, an epochal transformation affecting the entire planet.

Teilhard emphatically stresses that this does not imply an anthropocentric view, seeing humans as the pinacle of evolution (as was the case in the static *scala naturae* view). Rather, we humans are pushed along by this development ourselves, we are subject to a relentless process of hominisation and collectivisation, culminating in the emergence of a global 'We': a planetary network of thought and interaction. Indeed, Teilhard has been credited, by Garreau (2005) and others, with predicting the internet: WWW as a global noetic structure. For Teilhard, humans are a bridge. We ourselves are pushed forward by the inevitable planetisation of the noosphere. A turn of profound importance is taking place throughout the world, and we are only beginning to realise its true dimensions. We have already entered a different world: more mobile, fluid and migratory than the world of agriculture. 'The future will decide what the best name is to describe the era we are entering', Teilhard tells us (p. 214), but he clearly seems to be pointing at what we nowadays often refer to as the Anthropocene.

But this does not mean that we humans are in charge. Rather, a sense of disquiet is coming over us. The emerging situation is without precedent in the history of life and therefore, more than ever before, we experience a fundamental existential anguish. An enormous challenge is looming up in front of us. Humans are not the centre of the universe, but rather a vector pointing towards an emerging, planetary unification of the world (p. 224). We are waking up to the fact that the planet itself is now becoming thoroughly humanised and technified: a process of intellectual and technological collectivisation and convergence, resulting in the emergence of a global humanity, empowered to initiate collective action. Somehow, our uneasiness must be transformed into active thinking, a combination of foresight and coordinated action. It is only by becoming aware of the basic dynamics of the evolutionary process that we can hope to play a constructive rather than a disruptive role. We must acknowledge that Darwinian evolution is becoming eclipsed by conscious transformation, by an active metamorphosis of the planet, a drastic reorganisation of the evolutionary process, and the noosphere is already producing a new wave of genetically modified organisms, which Teilhard refers to as neo-life (p. 250). Increasingly, the noosphere will reorganise natural selection, via a computer-based, electronic self-consciousness, which increasingly will be superimposed on Darwinian heredity (cf. Zwart 2009, 2012).

17.3 A Teilhardian View of the Operator Theory

This calls for a drastic reorganisation of scientific research itself as well, Teilhard argues, which has to be transformed into a kind of planetary organisation, allowing for global teamwork. Notably in science, individuality must give way to technology-based hyper-reflection and hyper-personalisation (p. 259). Individual egos will dissolve into a distributed, super-centralised network of thought (p. 262). And this will affect the role and fate of philosophy as well, which should no longer be regarded as a solitary calling, but rather as a collective endeavour, as distributed, transdisciplinary form of reflection, involving multiple voices working in various places, but based on a clear awareness of the dynamics and the direction of the processes involved, so that it becomes possible to identify and consciously shape the next stage.

The operator theory is an effort to empower us to achieve exactly this. Whereas Teilhard was convinced that we are heading for the Omega Point (a theological, eschatological concept),[3] the operator theory rather predicts that the next stage will entail the emergence (already unfolding) of a noospheric global network of robotics and ICT, increasingly marginalising and replacing us.

References

Bachelard G (1938) La formation de l'esprit scientifique: Contribution à une psychanalyse de la connaissance objective. Vrin, Paris

Garreau, J (2005) Radical evolution: the promise and peril of enhancing our minds, our bodies – and what it means to be human. New York: Broadway Books.

Gould SJ (1977) Ontogeny and phylogeny. Belknap, Cambridge

Sloterdijk P (2009) Du musst dein Leben ändern: Über Anthropotechnik. Frankfurt am Main, Suhrkamp

Stikker A (1992) The transformation factor. Towards and ecological consciousness. Element, Rockport

Teilhard de Chardin P (1955) The phenomenon of man. Harper, New York [Le phénomène humain. Paris: Editions du Seuil]

Teilhard de Chardin P (1957) Le Milieu Divin: Essai de vie intérieure. Editions du Seuil, Paris

Zwart H (2009) From utopia to science: challenges of personalised genomics information for health management and health enhancement. Med Stud 1(2):155–166

Zwart H (2012) On decoding and rewriting genomes: a psychoanalytical reading of a scientific revolution. Med Healthc Philos 15(3):337–346

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[3] More fully elaborated elsewhere (Teilhard de Chardin 1957) as the 'pleroma', the fullness of time.

Chapter 18
In Response to the Reflections of the Reviewers

Gerard A.J.M. Jagers op Akkerhuis

Abstract Through their in-depth and multifaceted comments the authors of the review chapters contribute in a major way to the discussions about hierarchy and self-organisation raised by this book. On the one hand, the comments support the idea of using the Operator Hierarchy as a backbone for analysing organisation in nature, and as a new ontology in which the concept of the operator offers a new way of speaking about units/individuals. On the other hand, some reviewers highlight theoretic aspects that have not been explained with sufficient clarity and ask questions about aspects that warrant further discussion. Both the affirmative and the critical perspectives may further the acceptation and/or development of the Operator Theory. The following paragraphs highlight the major remarks of the reviewers, and offer a selection of answers to questions and responses to constructive criticism.

18.1 In Response to Barendregt (Chap. 3): The Operator Theory

Henk Barendregt analysed the logic of how dual closures results in the operator hierarchy. Barendregt views the operator theory as a meta-theory, a concept which is well known in mathematics. Meta in the example of the Operator Theory implies that the theory first groups objects into kinds, and then analyses the regularities in the relationships between these larger groups of objects of a similar kind.

We summarise some of the subjects that Barendregt focused on in his review (Chap. 3). First, when discussing the rules for the levels in the Operator Theory, which is abbreviated by Barendregt as O-theory, he remarks that:

"We have in general the following.

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DOI 10.1007/978-3-319-43802-3_18

1. The objects of a given level are being transformed, forming objects of varied complexity.
2. Some of these interactions from a circular transformation, like (*).
3. This circular reaction may be protected by a container, functioning on the basis of the given reaction and mediating the relationship between the contained processes and the world.

The combination of the circular reaction and its supported and supporting container is called an operator, and signifies the next level in the hierarchy. And then the story repeats." (Barendregt Chap. 3).

Another aspect that was emphasised by Barendregt was the role that higher level operators play in the production of operators of lower level kinds. Barendregt observes that: "For example, a complex biochemical molecule (like a vitamin) most probably will not arise in the evolution of atoms and molecules. It needs the more complex next step, the living cell, to be evolved. But then of course it can be considered on the previous level, after isolation. Similarly an organ like a liver appears only on the level of living organisms, after which it can be taken out. I would suggest to refer to objects like mentioned x as 'higher-order'. They exist at level, say, n, but can be evolved only by going to level n + 1." (Barendregt Chap. 3).

No critical discussion points were raised by Barendregt, which can be taken as a sign of Barendregt's support of the Operator Theory.

18.2 In Response to van Straalen and Gremmen (Chap. 5): An Analysis of the Graph-Pattern for defining Darwinian Evolution at the Smallest Scale

Van Straalen and Gremmen start their discussion with indicating that they agree with the suggestion of this book that the conceptual core of Darwinian evolution can be defined by means of an object-based graph-pattern, and that they find the suggestion of defining Darwinian evolution by means of a graph attractive for two reasons: (1) it helps to easily generalise the concept of Darwinian evolution outside the realm of organisms, and (2) it may help to overcome tautologies and circular arguments.

In addition they suggest improvements of the representation of the graphs, and ask critical questions about the use of the concept of failure of derivation, and about the links between the abstract representation of Darwinian evolution by a graph and existing narratives about various aspects of evolution.

18.2.1 Improvements of the Graph Pattern

Van Straalen and Gremmen suggest that the graphical representation of the Darwinian graph-pattern at the smallest scale can be improved. Their suggestion for improvement entails that an arrow must not be used without that there is an object at the end.

This suggestion offered a valuable contribution to the quality of the graphs in this book. Based on this suggestion all relevant figures in following chapters are adapted.

Their second remark in relation to the graph was that on philosophical grounds: “It is empirically impossible to test ‘failure of derivation’ because only refutation of ‘failure of derivation’, by showing a successful derivation, is logically possible.” This argumentation seems to focus in a rather stringent way on the logical positivist stance that only things that “happen” can be measured. While in principle things that do not happen cannot be measured, one may additionally argue that if an organism can be observed (e.g. through video) during all the moments of its life, for example because the organism lives in a cage, or in a petri dish, it should be possible to confirm through observation that the organism died while not having produced offspring. This would be similar to observing that a box is empty, because there are no objects in it. Potentially, such observations could be considered as proof that no derivation took place during the finite existence of an object, which proof would equal a test of the non-occurrence/failure of derivation. Because of practical obstacles, it can be difficult to obtain proof under natural circumstances that an organism has died before producing offspring. Such practical reasons, however, channel the argumentation towards feasibility, which is a different focus than a discussion about in principle possibility or in principle impossibility.

18.2.2 Links with the Evolutionary Narrative

The quest for simplicity that was followed in this book has resulted in a definition of Darwinian evolution that was stripped to its bare essentials. Any contextual information was eliminated on purpose. What remains is represented by a graph that—in biology—describes the relationship between a parent and two offspring, while of these offspring one realises reproduction in advance of mortality, while the other fails to do so.

Van Straalen and Gremmen observe that as the result of a minimal representation, well known aspects of the narrative of Darwinian evolution are fading into the background, including for example natural selection, mutation and recombination, genetic drift and development.

Luckily, it is not difficult to demonstrate that a minimalistic approach can be linked to all these important aspects, as demonstrated in the next paragraphs, starting with mutation, recombination and genetic drift. In principle aspects like mutation and recombination are parts of the derivation process, as discussed in Sect. 4.3.5. In that paragraph we discuss the mechanisms that contribute to derivation in a general way. When focusing on organisms, derivation may involve mutation, recombination etc. Technical details of these processes can be found in many textbooks about biology or genetics. Genetic drift demands a separate discussion, at a level of abstraction that can be viewed as residing “above” that of the Darwinian pattern (see top line of Fig. 16.3). When looking at genetic drift the focus shifts from a single pattern of evolution to a meta-level analysis of how many such patterns contribute to changes in gene frequencies as the result of random effects on survival of a group of organisms that is viewed as a population.

What remains to be discussed are the topics of natural selection, sexual species and development. In Chap. 6 we discuss extensions of the smallest scale model, using the examples of developmental histories and sexual reproduction. And in Sect. 16.2 environmental feedback is discussed as input for effects on survival that lead to the emergence of the pattern of selection. This discussion took into account the many new factors that are considered by the extended evolutionary synthesis.

The above responses to the questions and suggestions of van Straalen and Gremmen may offer some confidence that the graph-pattern of Darwinian evolution at the smallest scale indeed serves its purpose, namely that it invites for specific discussions of all aspects that contribute to the pattern of evolution, and assists in increasing the transparency of discussions. It is expected that such specificity and transparency will continue to support technical development in the future, while the object-based graph-pattern of Darwinian evolution will emerge as a unifying theme for existing narratives about evolution.

18.3 In Response to Reydon (Chap. 7): A Critical Assessment of the Generalization of Darwinism When Object-Based Graphs Are Used as a Basis

Reydon has contributed to this book by writing a critical assessment of the chapter in which a novel view is offered of generalised Darwinism. The critical philosophical analyses of Reydon offer a valuable check of the innovations that were suggested. Reydon starts his comments with a detailed explanation of the difference between universal Darwinism and generalised Darwinism, and continues with a contribution that focuses on the epistemological and ontological challenges that one encounters when defining Darwinian evolution by means of an object-based graph-pattern.

As Thomas indicates, universal Darwinism was introduced by Dawkins (2008) and suggests that the kind of Darwinian evolution that is found on earth can occur in any system of living beings, anywhere in the universe. The challenges of universal Darwinism are to define the living being, to find out about the potential of life on other planets, and whether such life would show evolution.

The Operator Theory offers new perspectives on how one can define the organism, and life. Using the scaffolding of the Operator Hierarchy organisms were defined as operators that hold an equal or higher position in the Operator Hierarchy than the cell (see Chap. 2). With the help of this definition of the organism as a basis, the analogy with water molecules (see Chap. 12) was used to define organismal life, or O-life, as a general concept that refers to the presence of dual closure in organisms. At the same time, in analogy with liquid water, the systemic view of life was defined as any system in which two or more organisms interact.

If one uses the Operator Theory as a basis, one can now deal in a structured way with the question of universality. In Sect. 12.8.1 it is discussed that measurements of spectral lines prove that the lower level operators in the Operator Hierarchy, such as atoms and molecules, have universal existence. Assuming that the logic of the Operator Hierarchy is not only generally valid at low levels, but also at high levels, the universal existence of low level operators suggests that potentially also the higher level operators have universal existence. If one now uses an object-based graph-pattern of Darwinian evolution in which every node represents an organism as defined by the Operator Theory, and if organisms like other operators have universal existence, this would offer an in principle proof of the universal nature of the pattern of Darwinian evolution.

Thomas also indicates that the processes of defining generalised Darwinism and Universal Darwinism face quite different challenges. In contrast to universal Darwinism, generalised Darwinism attempts to generalise the concept of Darwinian evolution to realms and processes outside biology. This implies that one has to define Darwinian evolution in a general way, and that one will have to identify a limited set of objects and situations that comply with this definition. A generalisation process of this kind urges for discussions about the links to existing theory, and about the ontological kinds of the objects of the object-based graph-pattern.

In relation to generalising Darwinism, Thomas suggests that a new approach, such as the Operator Theory must in principle comply with all the existing theory, because of what Thomas indicates as “theoretical adequacy”. Moreover, it is claimed that the evolutionary pattern that is suggested by the Operator Theory must comply with different ontological domains, which subject Thomas refers to as “empirical adequacy”. Moreover, Thomas warns that an approach should not be “overly a priory and insufficiently naturalistic”.

As a general response to the questions about theoretical and empirical adequacy and about insufficient naturalism, we ask attention for the discussion in Sect. 16.1 of the scientific method, notably Poppers hypothetico-deductive method. Popper’s method assumes that scientists use a combination of inductive and deductive methods to create hypotheses which can be checked for failure by confronting them with observations. In our view, to fulfil the criteria of theoretical and empirical adequacy one must start with stringent definitions. The reason for this is that as long as one lacks stringent definitions, examples cannot be selected in a stringent way, and as long the selection of examples is not stringent, one cannot derive a stringent definition from such data. Such a catch-22 implies that when using deduction, one will generally start with preliminary definitions, also called folk definitions, which allow for the selection of preliminary observations, which result in preliminary hypothetical constructs the quality of which must subsequently be falsified. This implies that one cannot avoid the working in an a priori way with some form of definitions.

When developing the theoretical construct of the object-based graph-pattern of Darwinian evolution it was never hoped for that this new approach would comply with any and all existing definitions, as demanded by theoretical adequacy. The reason for this is simple: one cannot be sure that already existing definitions would offer a uniform context. At the same time, and as we discuss in Chap. 2, the new definition was deliberately designed in such a way that its assumptions would be open to ontological discussions, both with respect to objects, relationships and patterns.

The aim of creating transparency about ontological aspects also unveiled new challenges and invited for new discussions. One of such challenges is now placed on the foreground by Reydon, namely that the ontological kind of the objects that are used in an object-based graph-pattern of Darwinian evolution cannot be generalised at will. In fact, the examples in Chap. 6 demonstrate that we have never generalised haphazardly the kind of a node in the graph. For example, in one example the nodes are replaced by developmental histories. Such histories do not represent physical objects, but represent a series of kinds that relate to physical objects in different developmental stages, and that are related through a developmental relationship. While the developmental history is no longer an object, but a "trajectory", we still consider this generalisation valid, because it is linked in every aspect to uniform kinds of an underlying physical system. Using the species concept as a negative example, we also discussed in Sect. 6.2.5 that nodes cannot be replaced by entities that are not of a uniform kind.

It seems furthermore that Reydon suggests that the relationships in the graph-pattern must represent interactions. Based on this assumption, Reydon suggests that "Kinds cannot interact with other kinds, only their members (as concrete individuals) can interact with one another. Thus, any kind-based graph in which species occur as the nodes would actually represent interactions between individual member entities of the species involved, rather than between the species themselves, except in the case in which species themselves are conceived of as concrete individuals."

First, we emphasise that we agree fully with Reydon that kinds are conceptual entities that cannot interact physically. Second, as we indicate in Sect. 6.2.5 we also agree with Reydon that species do not fit in with the graph approach. In addition we draw attention to the fact that a derivation relationship in the graph-pattern of Darwinian evolution must not necessarily represent a physical interaction. For example, if a drawing is copied by a child, the derived drawing has never physically interacted with the original. Also when the patterns of variation or selection are assessed, such an assessment does not involve a physical relationship. These examples indicate that relationships in the object-based graph-pattern of Darwinian evolution can represent more abstract relationships than interactions. In our view, the fact that the relationships in the graph can be more general than just interactions may resolve the criticism of Reydon. At the same time, and in line with Reydon, we think that it is very relevant that ontological discussions are held about the kinds of objects and relationships that can figure in a graph-pattern of Darwinian evolution. This is a relatively new subject that may still profit from philosophical contributions.

18.4 In Response to Vromen (Chap. 9): In Defence of Gradualism When Defining the Organism Concept

In his commentary Vromen questions four aspects of how the Operator Theory defines the organism concept. The first aspect that is questioned is the possibility/impossibility of assessing the adequacy of a definition when there is no clarity about the context for its intended use. The second aspect focuses on the link between closure and the more traditional criteria for organismality, such as metabolism and reproduction. The third aspect focuses on the necessity of physical integration. And the fourth aspect aims at defending the utility and quality of the criteria that gradualists use when assessing the degree of organismality of a system.

18.4.1 Context

The context of the definition that is suggested by the Operator Theory was not explained in detail in Chap. 8. In the introductory chapter, however, it is indicated that the general context of this book is one of simplicity and generality. Simplicity refers to the aim of reducing the number of criteria to a minimum. As indicated in Sect. 1.4.1 this book follows Einstein when he says that: "It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience (Einstein 1934, p 165)." From this perspective, we suggest that the Operator Theory can be viewed as a stringent and relatively simple method for the identification and ranking of all the operators. Meanwhile, the logic of the operator theory is based on a limited set of only two criteria, namely functional and structural closure, which in interaction are referred to as dual closure. Other hierarchical rankings of objects generally make use of more criteria, e.g. the example-rankings that are discussed in Sect. 16.1. And once that the concept of the operator has been defined, the hierarchy of the operators can be applied as a foundation for a stringent and simple definition of the organism concept as follows: any operator of the level of the cell or higher in the operator hierarchy represents an organism.

By using the operator based definition one automatically avoids the catch-22 that sometimes plagues other definitions of the organism: as long as one has only access to folk-definitions of the organism concept, one cannot be sure that the set of things viewed as organism is logically/ontologically homogeneous, and as long as there is no certainty that the set of organisms is logically homogeneous it is difficult to be sure about the quality of any definition of the organism concept that is deduced from this set. The Operator Theory suggests solving this catch-22 situation by accepting the operator hierarchy as an external scaffold for defining all the operators, and by applying this scaffold for defining the organism concept. Now, the organism concept can be defined without any reference to list of objects deemed organisms. The utility of such an externally based approach can be assessed in the context of the simplicity and generality of the resulting definition compared to the simplicity and generality of other definitions.

18.4.2 Link with Closure

The second aspect that Vromen discusses is that people may find it easier to accept the definition of the organism concept based on the Operator Theory, if it can be demonstrated that a clear relationship exists with the more traditional criteria that have been used to define organisms, such as metabolism and reproduction. This remark begs for further elucidation of the relationship between dual closure and classical criteria for organisms and life. We refer to organisms and life, because the literature seems to mix criteria for the concepts of organism and life. When discussing criteria for life, such criteria frequently show overlap with properties of organisms. For example Koshland (2002) suggest the following seven "pillars" of life: program, improvisation, compartmentalization, energy, regeneration, adaptability and seclusion.

To explain the link between the criterion of closure and the criteria represented by for example the seven pillars of life, we start with dual closure. As explained in Chap. 2 dual closure combines (homogeneous) functional and structural closure. The specific forms of structural and functional closure depend on the level of complexity of the operator/organism. In organisms of the kind cell, the dual closure involves the interaction between the autocatalytic set and the membrane. In the endosymbiont cell, the dual closure involves the functional closure of the obligatory interactions between the host and the endosymbiont (e.g. a mitochondrion or chloroplast) and the structural closure of the membrane of the host cell. In multicellular operators the interacting cells are unified because of the structural closure of a common membrane, which emerges as soon as plasma connection between cells are formed, while the functional closure emerges through the obligatory exchange of material through plasma strands. At the memic level the functional and structural closures are represented by the neural interactions and a sensory interface, respectively. While the criterion of dual closure is constant between levels, the specific form of the dual closure depends on the level in the operator hierarchy. As the specifics of dual closure differ between levels, it is not possible to indicate a single relationship between dual closure and the classical criteria for the organism or life. Yet the following more or less general relationships can be observed.

If one focuses on the cell, and looks at the criteria of metabolism and reproduction, these can be viewed as the consequences of autocatalytic closure. While details are discussed for example in Sect. 14.1, one can say that autocatalysis will more or less automatically lead to growth and reproduction if resources are available in sufficient amounts. This shows that if autocatalytic closure is used as a starting point for defining organisms, other properties such as metabolism and reproduction can be viewed as derived/associated qualities. By analogy autocatalysis can be viewed as the origin of for example program, improvisation, energy, regeneration and adaptability, while the membrane of a cell can be viewed as the origin of criteria such as compartmentalization and seclusion.

In the context of how one can decide about criteria, it is relevant that—as discussed in Sect. 2.7.1—the Operator Theory aims at using criteria that lead to a stringent definition of the organism concept, such that all organisms are included, and all non-organisms are excluded. If one uses for example the individual criteria of program, energy, adaptability etc. such criteria may include all things deemed organisms, but by itself each of these criteria does not exclude non-organism systems. One could now suggest that when the seven criteria are used in combination, they can be viewed as a sufficient basis for including all organisms and excluding all entities that are not organisms. However, such a suggestion is debunked, because the seven criteria fail to include as organisms a frozen bacterium and a dry seed, because while in a frozen state both the bacterium and seed will fail many of the criteria of the seven pillars. Neither will a frozen bacterium or a dry seed show reproduction. The use of combinations of many criteria can also be criticised from the simplicity point of view. As discussed in Sect. 16.1 one can use Ockham's razor to analyse how many criteria the classical approach and the operator-based approach need to arrive at a stringent definition. Such a test would demonstrate that the operator-based definition arrives at an unambiguous demarcation of the organism concept while using only a few criteria, whilst classical viewpoints generally combine many criteria without arriving at an unambiguous demarcation.

18.4.3 Physical Integration

A fundamental aspect of any operator is that its dual closure implies a state of physical integration. Using the operators as a basis, one can additionally recognize other physical units that are called compound objects (see Chap. 2). By creating clarity about whether physical units are of the kind operator or of the kind compound object, the Operator Theory adds a fundamental tool to the toolbox of philosophers and system scientists. Using the operator concept as a foundation, one can focus on the organisation inside an operator, called inward complexity, or focus on the complexity between operators of different kinds, called upward complexity, or focus on the organisation of systems of interacting organisms, called outward complexity. If this three-dimensional framework is accepted as a starting point, this can bring clarity in the classification of for example a flock of birds. The flock of birds is not an operator, and its complexity therefore should be analysed as a system of interacting operators, and thus along the outward dimension. This conclusion is independent of the distance between the observer and the flock of birds.

18.4.4 Degrees of Organismality and Holobionts

From the information in Chap. 8 Vromen concludes that the Operator Theory aims at a definition that can in a binary way distinguish whether something is an organism or not. Vromen also observes that the logic of a binary viewpoint contradicts the gradualist viewpoint, according to which an entity can more or less organismal.

In the context of the above differences in viewpoints, it is of marked importance to notice that the Operator Theory is not blind to gradual events. For example, a group of entities may slowly develop towards an integrated state. An example of such development is the development of the human embryo. The first steps in the development the zygote involve three cell divisions, resulting in an eight-celled stage. The question whether these eight cells represent an organism is answered by the Operator Theory with “no” or “not yet”. The reason is that the cells may without problems separate and develop independently. A few hours later, dual closure is established after the cells have formed plasma strands. The Operator Theory thus speaks about a gradual development through different stages of complexity, while dual closure offers a hallmark that allows one to in a binary way distinguish whether or not certain stages represent a single operator/organism. According to this perspective, a practical link with the gradualist viewpoint can be created by the suggestion that one can speak about different degrees of "integration" or "interaction" of entities, while only a specific form of integration/interaction represents dual closure.

We now use these insights for analysing the interaction of a randomly chosen organism with associated microbes. Such an interaction has also been named a holobiont. If one uses the operators as the basic units for analysing holobiont interactions, it is relatively easy to delineate the limits of the organism. For example if we speak about a protozoon with obligatory bacterial endosymbionts, we can recognize dual closure, due to which the protozoon and endosymbiont(s) are viewed as an operator of the kind "endosymbiont cell" (see also Chap. 2). Once the basic structure of the protozoon is defined by means of dual closure, it becomes possible to classify all bacteria that live on its membrane as not being part of the protozoon, but as residing in the environment that surrounds the protozoon. Such bacteria classify for example as parasites, or symbionts, or mutualist, but they are always viewed by the Operator Theory as operators that the protozoon interacts with, not as parts of the protozoon. Potentially such interactions with external bacteria may lead to coevolutionary relationships. And in some cases, for example when unicellular protozoa that already had mitochondria additionally obtained chloroplasts and became algae, very close interactions may lead to an obligatory secondary endosymbiont relationship, after which the Operator Theory classifies the ensemble as an endosymbiont operator that harbours two kinds of endosymbionts.

The above also demonstrates that the Operator Theory distinguishes between two different uses of the concept of a holobiont. The first use is that of an obligatory endosymbiont relationship, such as a protozoon with mitochondria, an alga with mitochondria and chloroplasts, or an aphid with mitochondria and endosymbiont bacteria of the species *Buchnera aphidicola*. All these examples of holobionts classify as organisms. The second use of the term holobiont refers to an organism that has facultative interactions with other organisms, e.g. on its skin or in its intestines. According to the Operator Theory such an ensemble does not classify as an organism but as a group.

18.5 In Response to Stoelhorst (Chap. 11): What the Operator Theory Adds to Major Evolutionary Transitions Theory

Stoelhorst has reviewed the comparison of the Major Evolutionary Transitions Theory and the Operator Theory, while focusing on groups of interacting organisms. Stoelhorst remarks that while he "immediately found OT's ontology in the form of the ‘Operator Hierarchy’ convincing” it was difficult for him to accept that “human social organisation does not qualify as a major transition”. Stoelhorst continues stating that for him the paradox was resolved once he recognized “that OT shows the need for a much finer-grained understanding of major transitions than METT currently offers”.

Additionally it is concluded that both theories hold different views on what constitutes a major transition. While the OT is “single-mindedly focused on delivering a coherent ontology based on transitions in individuality only, METT attempts to unravel the nature of complexity by combining an interest in three different aspects of reality: individuality, the evolution of informational systems, and the unit of selection in evolution.” Stoelhorst also observes that the OT is primarily axiomatic and deductive, while METT is primarily descriptive and inductive. Because of such differences the two theories necessarily must arrive at different notions of what constitutes a (major) transition.

Following this conclusion Stoelhorst asks how the use of closure by the OT may contribute to our understanding of (major) transitions, while advocating that the OT seems “to offer a much more convincing account of one of the three storylines in METT’s ‘3D account’ of major transitions, namely the storyline of the evolution of individuality.” For this conclusion Stoelhorst offers the following three reasons: (1) the elegancy of the OT, (2) the extension of the OT downward to inorganic matter and (3) the fact that the OT pinpoints a number of ambiguities in METT. Examples of such ambiguities are: some major transitions were added to METT over time, some major transitions were removed from METT over time, and METT is not conclusive about human eusociality and its status as a major transition. According to Stoelhorst these three ambiguities “fall nicely into place when seen through the lens of OT, which denies them status as major transitions in individuality.”

Stoelhorst continues working towards the link with social research by citing Szathmáry (2015) who explains the 2D account of METT (individuality, the evolution of informational systems) as follows: “I think this dual approach is a feature rather than a bug. It would be somewhat surprising if major achievements of evolution could be satisfactorily coerced into a Procrustean bed of either dimension”. While supporting this position, Stoelhorst indicates that this position is also “entirely compatible with an interest in further unravelling one of these dimensions and then seeing how advances in our understanding of that particular dimension, *in casu* individuality, may affect METT’s overall interpretation of major transitions”.

In this context Stoelhorst concludes that the OT may lead to a finer-grained overall understanding of major transitions because it leads to the following insights: (1) The use of “upward”, “outward” and “inward” dimensions of the evolution of biological complexity allows for fine-grained analyses of transitions, and (2) “Individuality”, “de-Darwinisation” and “levels of selection” are not one and the same. Based on these insights Stoelhorst concludes for example that “human social organization based on natural language is a major transition along the outward dimension, resulting in a new level of selection. But it does not involve de-Darwinisation, nor does it constitute a transition in individuality.”

18.6 In Response to Russell (Chap. 13): Adding (Thermo-) Dynamic Aspects to Definitions of Life

After summarising the concepts of O-life and S-life, Russel suggests that: “What, in my opinion, could be added to the above viewpoint is that, in terms of the Second Law of Thermodynamics, both an organism, the agent that complies with O-life, and an ecosystem, which complies with S-life, may be considered, like other active dynamic phenomena in the Universe, as engines of entropy generation, i.e. both work within Boltzmann’s Statistical Entropy Law (and see Schrödinger 1967)” (Russell, Chap. 13).

Subsequently, Russell expands on the viewpoint of the Operator Theory by offering a link with functional criteria that are typical for organisms on earth. According to the current perspective, Russell adds the important insight that because humans are feeding generalists, feeding in part on vegetables and in part on animal tissues, food has always been viewed as the ultimate fuel for organisms, while life became a synonym of heterotrophy. However, the evolutionary tree roots in the physical world, and at the base of the tree one finds only autotropic organisms.

Russell further remarks that: “Only by knowing and understanding how chemosynthetic life first emerged and, from a branch of this life, how oxygenic photosynthesis first onset, can we grasp fully the why and how of all the mechanisms that occur in organisms and, through interactions between organisms, how organisms feed from, and back, to their co-evolving environment, in ecosystems. These are the required foundations that should be made clear in the first chapters to all and any science books about organisms and their ecology.”

The suggestions of Russell have inspired us to add to this book additional chapters on thermodynamics.

18.7 In Response to Georgiev and Chatterjee (Chap. 15): Closure, Self-Organization and Time Dependence

The perspective of Georgi and Chatterjee adds many new viewpoints to the chapters about thermodynamics (Chaps. 13 and 14). In their research they work towards a common approach to definitions of life, quantity of organization, evolutionary stages and levels of complexity. It is suggested that the Principle of Least Action can offer a general logic for linking many different aspects of thermodynamics and self-organization into a common approach. Indeed the principle of least action may well offer a general foundation. At the same time, the results of Chaps. 4 and 12 of this book suggest that it may be relevant to keep in mind the ontological kinds of the concepts that one aims at relating. After all, because action is defined as the product of work and time, the SI units of the least action principle are Joules times seconds. Meanwhile, in this book Darwinian evolution was defined as a pattern. And life was defined in two ways: (1) as a general indication of the presence of a specific property that only the operators have that are complex enough to be called organisms, and (2) as a system of interacting organisms. This small inventory of kinds of concepts suggests that if one would aim at linking the principle of least action to life, quantities of organization and to evolution this would most likely demand an indirect approach that would be based on translations from the least action ontology to several other ontologies that are in use for describing for example patterns, properties or systems. With respect to evolution, such a translation may presumably be facilitated by focusing on the process of generational morphing as introduced in Sect. 14.1.5 and discussed in Sect. 16.3, after which specific results of generational morphing processes can be related to one or more examples from the family of Darwinian evolution patterns. Preliminary philosophical explorations like these suggest that while the principle of least action can offer a valuable foundation for integration, interesting ontological puzzles may still have to be solved in the process of connecting the principle of least action to concepts such as life, self-organisation and evolution.

Georgi and Chatterjee furthermore examine the links between feedback loops and self-organisation. They indicate that closure links closely to "… the positive and negative feedback loops between the interfunctions in self-organizing systems that increase their action efficiency and evolutionary hierarchy (Chatterjee 2015)". Without such loops, they indicate, it may be impossible for a complex system to self-organize. If one views closure as a special feedback loop, and as an integrating topic, the methodologies suggested by Georgi and Chatterjee may potentially be integrated with the Operator Theory and with for example the theory about Ouroboros equations as has been suggested by Soto-Andrade et al. (2011).

18.8 In Response to Zwart (Chap. 17)

Zwart starts his reflection chapter (Zwart, Sect. 17.1) with a sketch of the contemporary debate about the desirability of approaches inspired by the idea of a scala naturae. There are many opponents who discard the idea that "certain levels of complexity can be discerned in nature, and that the history of life and evolution is characterised by a basic tendency towards increasing complexity". Zwart also indicates that "Against the backdrop of this polemical debate between critics and adherents … the Operator Hierarchy constitutes a provocative gesture. It aims to rehabilitate the scala naturae idea by recasting it in scientific and biological terms, in close dialogue with insights from contemporary research fields. From this perspective one could argue that the Operator Theory seems congruent with an important precedent, namely the view of Teilhard de Chardin …"

The work of Teilhard de Chardin (1959, 1969) ranks abiotic particles, single-celled and multicellular organisms and a future holistic state for society, Point Omega. Indeed some ideas of Teilhard de Chardin are congruent with the Operator Theory.

As Teilhard de Chardin focussed on particles, he was able to integrate transitions between physical and biological particles into one large sequence. For Teilhard de Chardin this sequence of increasingly complex particles corresponded with chronology and with the genesis of the universe (Teilhard de Chardin 1996). Fundamental to the work of Teilhard de Chardin were his ideas about "complexification intériorisante", or inward complexification. Viewing complexity as the product of relationships of elements amongst themselves he arrived at the following two insights.

"First, in the multitude of things comprising the world, an examination of their degree of complexity enables us to distinguish and separate those which may be called "true natural units", the ones that really matter, from the accidental pseudo-units, which are unimportant. The atom, the molecule, the cell and the living being are true units because they are both formed and centred, whereas a drop of water, a heap of sand, the earth, the sun, the stars in general, whatever their multiplicity or elaborateness of their structure, seem to possess no organisation, no "centricity". However imposing their extent they are false units, aggregates arranged more or less in order of density.

Secondly, the coefficient of complexity further enables us to establish, among the natural units which it has helped us to "identify" and isolate, a system of classification that is no less natural and universal (Teilhard de Chardin 1969, p. 137).

Close correlations can be observed between the concepts of "formed" and "centred" on the one hand, and "structural closure" and "functional closure", on the other. Likewise, the concepts of "true units" and "false units" correspond with "operator" and "interaction system", respectively. Such relationships are a testimony of the conceptual similarity between the insights of Teilhard de Chardin and the theoretic foundations of the Operator Theory.

The Operator Theory also adds novel insights. For example, Teilhard de Chardin assumed correspondence between complexity and consciousness, such that for him talking about the complexity or the consciousness of an atom were the same. The Operator Theory now suggests that consciousness is a property that is linked to operators with a memic architecture. Such architecture allows integrative calculations that take place in networks of neurons or in technical networks with equivalent functioning. Accordingly, the concept of consciousness does not apply to operators below the level of the memon. Also Ulrich (1972) has concluded that the concept of consciousness of Tielhard de Chardin suffers from overextension.

Teilhard de Chardin also assumed that evolution would reach some sort of zenith in a highest state of consciousness, called Omega (Teilhard de Chardin 1959), which can be viewed as a synonym for a highest level of complexity. From the point of view of the Operator Theory, Omega does not automatically fit in with the ranking of the operators according to dual closure steps. The reason is that Omega would be based on interactions between organisms with brains, named "memons" in the Operator Theory. As it would consist of interacting memons, a system like Omega would represent an interaction system, and not a next operator. Omega could only represent an operator if the interactions would allow for dual closure. There is a single option in Fig. 18.1 that corresponds with this path, which leads from the memon straight to the right. All the other paths would first involve more complex operators. And like few examples exist of the direct path from the cell to multicellularity (from bacteria to blue-green algae), which indicates technical difficulties, the path directly towards the multicellular memon may be even more difficult. From the perspective of the Operator

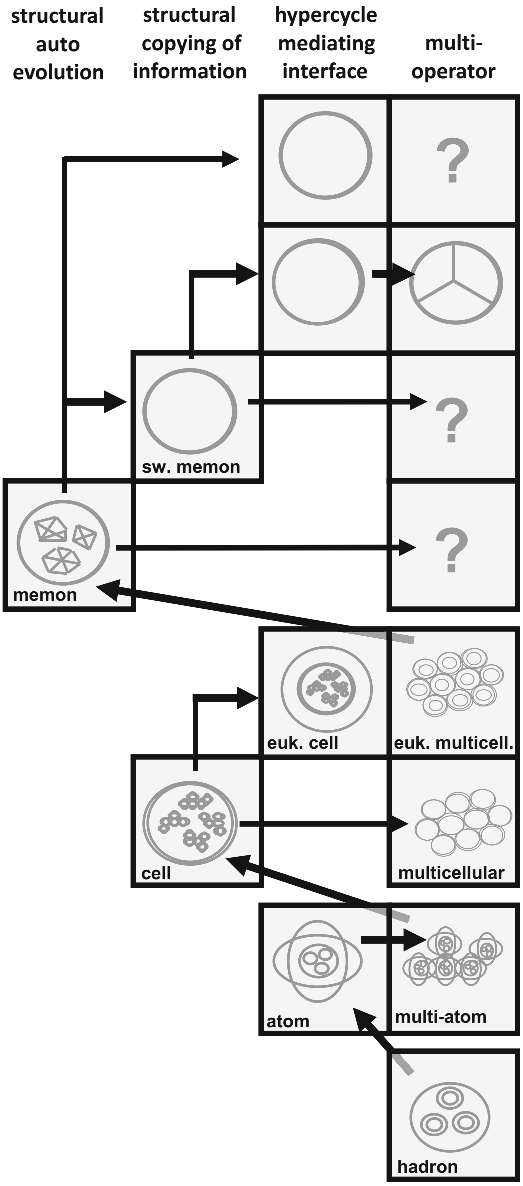

Fig. 18.1 A basic representation of the Operator Hierarchy in which extrapolations are included for seven kinds of memic operators that may form in the future. *SW-memon* = softwired memon. The terms on *top of the columns* indicate different "closure dimension" (explanation in Sect. 2.6.1). *Empty circles* indicate future operators. A *circle with three sections* indicates a multi-memon. If a *box contains a question* mark, this indicates that it is assumed that the system presumably has a low probability of being formed. The empty space between *boxes* is an artefact resulting from the re-organisation according to closure dimensions (see Fig. 2.2 for explanation). *Thin lines* represent transitions that are deemed relatively complicated

Theory it is therefore highly unlikely that Omega represents an operator. So what would be the next operator, and how can it be predicted? Extending the Operator Hierarchy may assist in the answering of this question.

The possibilities of extrapolating the Operator Hierarchy were explored in Jagers op Akkerhuis (2001). This section adds some recent insights. First, however, it must be indicated that the Operator Theory is a new theory. With the current state of affairs this new theory has allowed contributions to the resolution of several long standing open questions, e.g. about the definitions of hierarchy, life, evolution and the organism. At the same time, many questions remain unanswered about the logic of the Operator Theory, notably about the exact nature of its higher order regularity, and whether or not this regularity can be modelled mathematically. Until the moment that such questions have been answered in a fundamental way, the application of the Operator Hierarchy as a basis for extrapolations towards future kinds of operators will to some degree remain speculative. This having been said, we in the following section assume that the logic of the Operator Hierarchy can offer at least a first glance of the world that presumably lies just beyond the current horizon of evolution.

As a basis for an extrapolation towards the next kind of operator Fig. 18.1 is used as a starting point. Figure 18.1 is a simplified version of Fig. 2.3 to which hypothetical positions for all the future memons were added. As explained in Fig. 2.2 and Sect. 2.6.2 a simple logic can describe the abstract increase in possibilities from a single hadron, to two operators based on atoms (the atom and the molecule), to four operators based on cells (the cell, the endosymbiont cell, and the multicellular forms of both), to an expected total of eight new operators at the memic layer. Of the memic operators, only the first kind has been realised so far, namely the "animal with brains", the memon, more specifically the hardwired memon. The name hardwired memon was chosen because "hard" physical "wires" connect all the neurons.

There are two assumptions that have to be made as a basis for the extrapolation towards a next, new kind of operator at the next level above the hardwired memon. The first assumption is that the Operator Hierarchy follows an exponential increase in possibilities than can be described by the algorithm that is explained in Sect. 2.6.2 and Fig. 2.2. According to this algorithm, the operators in the rightmost column of Fig. 18.1 would all possess a specific closure of the kind A, while the operators in the second column from the right would possess a specific closure of the kind B etc. Accordingly, the next operator at the memic layer, which is the operator we try to predict here, would possess a specific closure of the kind C, which, at a lower layer, would also be present in the cell.

The second assumption concerns the translation from the abstract properties that are predicted by the algorithm to real-world properties. The challenge is to deduce from the operators in a specific column of Fig. 18.1 the hypothetical common property that is predicted by the algorithm. It is relatively easy to meet this challenge if we look at the first column of Fig. 18.1. Every operator in this column consists of two or more objects, mostly operators, of a uniform kind. In this sense, they can be viewed as all representing a multi-object quality. If, however, one aims at predicting the common property of all the operators in the second column from the right in Fig. 18.1 there are not four, but only two examples. This implies that it becomes more difficult to identify the common property, and that one can be less certain about the result of the deduction. Acknowledging such limitations, the Operator Theory has settled on the concept of Hypercycle Mediating Interface, which refers to the observation that both the atom and the endosymbiont cell add a separate (additional) interface to the organisation of the system.

Finally, it is even more difficult to deduce the property of the third column from the right in Fig. 18.1, because this column contains but a single example. In fact, the uncertainty about the exact kind of property is the reason why several options can be suggested. One option, which has been followed in the publications about the Operator Theory so far, is that one can focus on the capacity of a cell to re-produce all molecules in the set, as a basis for maintenance or reproduction. If one views the set of catalytic molecules as the cell's information, this implies that the cell is autonomously capable of copying its information. And because this process involves the copying of the structures of the catalytic molecules, the process can be viewed as the structural copying of information. Another option may be to focus on the structures of the catalytic molecules as units of information. These two possibilities lead to slightly different extrapolations.

One extrapolation would be to assume that the new memon would possess neural structure. However, to comply with the criterion of structural copying of information the memon would have to be able to copy all the information in its neural network in a structural way. This means that by copying the structure of its networks it would have copied all the knowledge inside this structure. While hard-wired memons, like humans, can educate other memons, this is not the same as copying the structure of a neural network. And neither can biological memons copy their knowledge during reproduction, because the egg and semen only contain genetic information, not neural information. Structural copying of information therefore is not an option for hard-wired memons. To enable the copying of a neural network as a structure, the information about the structure of the network and the strength of the connections between the neurons would have to be available in the form of a data file that could be read and copied to a next "body". This kind of structural copying differs markedly from communication, which does not involve the copying of neural structure. As it needs access to data-files of the neural network, this kind of next level memon would necessarily have to be technical.

Another prediction would focus on the catalytic molecules in the cell and view these as structures that symbolize units of information. As the new property of cells one could now assume unit-wise information processing. Such a direct connection between structure and information is not present in the brain of hard-wired memons, because in the neural network the symbolic value of the information is distributed throughout the network. However, this may change if a next operator can by technical means use units of information, e.g. concepts, and connect these as a means to process information. Again such a next kind of operator would have to be technical to allow for this option.

References

Chatterjee A (2015) Thermodynamics of action and organization in a system. Complexity. doi:10.1002/cplx.21744

Dawkins R (2008) Why Darwin matters. The Guardian, Saturday 9 February 2008

Einstein A (1934) On the method of theoretical physics. Philos Sci 1:163–169

Jagers op Akkerhuis GAJM (2001) Extrapolating a hierarchy of building block systems towards future neural network organisms. Acta Biotheoretica 49:171–189

Koshland DE Jr (2002) The seven pillars of life. Science 295(5563):2215–2216. doi:10.1126/science.1068489

Schrödinger E (1967) What is life? Cambridge Univ Press; with a Forward by Roger Penrose, (first published 1944)

Soto-Andrade J, Jaramillo S, Gutierrez C, Letelier J-C (2011) Ouroboros avatar: a mathematical exploration of self-reference and metabolic closure. European conference in artificial life, ECAL 2011, Paris

Szathmáry E (2015) Toward major evolutionary transitions theory 2.0. PNAS 112:10104–10111

Teilhard de Chardin P (1959) The Phenomenon of Man. Harper, New York. (Original: Editions du Seuil I, Paris, 1955)

Teilhard de Chardin P (1966) Man's place in nature. The human zoological group. Collins, London. (Original: Editions du Seuil VIII, Paris, 1949)

Teilhard de Chardin P (1969) The future of man. Collins, London. (Original: Editions du Seuil V, Paris, 1946)

Ulrich LP (1972) The concept of man in Teilhard de Chardin. Ph.D. thesis, University of Toronto, Canada

Chapter 19
Contributions to Open Challenges in Systems Theory and the Life Sciences

Gerard A.J.M. Jagers op Akkerhuis

Abstract Based on the foundations of the Operator Theory, the chapters of this book discuss contributions to several fields of science. This summary chapter lists the most important contributions.

The following paragraphs offer a summary of what can be viewed as the major contributions of the Operator Theory to the sciences.

1. Defining units

   The concept of the operator has added a new perspective to the broad range of existing viewpoints on individuality, such as object, individual, Holon, token, unit, whole, entity, and unit of selection. Because of the criterion of dual closure, the unity of every operator is defined in a very stringent way, both physically and dynamically. Because of this, the operator concept offers a fundamental basis for the analysis of interaction systems, which can be compound objects that consist of physically attached operators, or groups that consist of non-attached operators.
2. Defining levels of organisation

   When ranking increasingly complex operators, every dual closure can be viewed as a well-defined step towards a next kind of operator. Such an operator of a next kind simultaneously resides at a next level of organisation. At the same time, and as is suggested by the DICE approach (see Sect. 2.7.3), the ranking of the operator hierarchy is not necessarily mirrored inside an operator or in the organisation of systems of interacting operators. Inside operators and in systems of interacting operators any ranking of levels of elements is relative, and

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_19

will depend on the wilful selection of a specific perspective. For example the same organisms reside at different levels in an ecosystem, depending on whether one constructs a ranking based on feeding relationships, or constructional relationships. Levels that are not based on closure or dual closure, such as the colours of the rainbow, will have to be chosen arbitrarily.

3. What is the distance between levels?

   The Operator Theory has added to system science a measure for the distance between one operator at a given level and the next kind of operator at the next level. The distance measure is related to the exact position in the operator hierarchy. Below the level of the hadron, the distance between two levels is determined by a single closure. From the level of the hadron and up, the distance is determined by dual closure. The use of single closure and dual closure offers a topological/structural criterion, and is more specific for this reason than conventionally used functional criteria, such as "powers of ten", or the triptych used in Major Evolutionary Transitions theory of: cooperation, competition reduction and reproduction as part of a larger unit.

4. The organism concept

   The endeavour of defining the organism concept has been plagued by two challenges. The first challenge is to find an alternative for the horizontal grounding (see Sect. 1.4) of the organism concept, which classically has led to a search for general properties of things which presumably are organisms. The second challenge is to get rid of the circular reasoning that organisms are living beings, while life is defined as a property of organisms. Both challenges can be dealt with if one uses the Operator Hierarchy as an external scaffold which offers an independent definition of different kinds of operators. While using this scaffold, all the operators that are of a kind which is at least as complex as that of the cell (as an operator) can be defined as representing organisms. Consequently, if an operator is of a lower level kind, it is not an organism.

5. Can life be defined scientifically?

   The concept of life has many homonyms. In principle, one needs a definition for every homonym. For this reason we do not aim at offering a single definition of life. The definitions of life that are supported by the Operator Theory focus on two applications of the concept in biology. We used the analogy with water molecules, and water as a fluid, to further investigate two applications of life that either refer to organisms (O-life), and life as referring to systems (S-life). As the definition for O-life we suggest: O-life is a concept that refers in a general way to the presence of dual closure in organisms (the organism has been defined under point 4). As the definition of S-life we suggest: S-life is a concept that refers to a system of two or more interacting organisms. While O-life does not demand dynamics, S-life does.

6. Darwinian evolution.

   Conventional approaches generally define Darwinian evolution with the help of criteria, such as reproduction, variation and selection, or as a measure for the outcome of evolution, such as changes in gene frequencies in a population over generations. The Operator Theory adds to this that it is possible to define the concept of evolution by changing the focus from a process to an individual-based graph-pattern. The graph pattern of Darwinian evolution at the smallest scale can offer a reference, a foundation, for a family of extended and generalised patterns.

7. Extending Darwinian evolution: a family of patterns.

   Based on an individual-based graph-pattern of Darwinian evolution at the smallest scale, extensions are suggested that included for example: a pattern of evolution that includes multiple generations, a pattern that includes sexual reproduction, a pattern based on kinds (which cannot be used for species), and a pattern that includes developmental histories, and a pattern that includes feedback and niche construction.

8. Including dual closure steps in Darwinian evolution.

   While on the one hand, Darwinian evolution is said to be the result of small genetic changes, the tree of life also includes larger changes in the construction of the organisms that are not only the result of mutations. Examples of such larger changes are: (1) the symbiotic emergence of the endosymbiont cell, classically indicated as eukaryote cell, (2) the emergence of bacterial and endosymbiont multicellulars, and (3) the emergence of organisms with brains. By applying the graph-pattern of Darwinian evolution it becomes possible to deal with both the small genetic changes, such as mutations, and the large changes, for example when a life history does scaffold the steps from a unicellular stage, to a colonial stage, to a multicellular stage.

9. Looking over the horizon of (meta-) evolution.

   The higher order logic of the Operator Hierarchy suggests that one day it will be possible to accurately extrapolate the hierarchy towards next steps. This is the first time in history that a method allows for specific hypothesis about such next steps. Replaying the ‘tape of evolution’

   While it is principally impossible to predict the occurrence in evolution of any specific species, or to preview how a particular member of this species would look like, the course of evolution on a meta scale may be much more predictable than is currently acknowledged by the scientific community. In our view, the restrictions of dual closure may be sufficiently stringent to guide any next replaying of the tape of evolution through the same steps in the Operator Hierarchy as have been realised currently.

10. Systems and objects.

    The Operator Theory suggests that whether or not an entity is viewed as a system or as an object depends on our intentions. The same entity can be viewed as a system, if it is our intention to analyse the object in a systemic way, or as an object, if it is our intention to classify the system as an object.

11. An object-based approach to the extended evolutionary synthesis

    The extended evolutionary synthesis aims at elaborating the classical evolutionary theory with a range of additional processes, including for example physical rules of construction, the impact of organisms on their environment, the effects of the environment on development, and the transfer of more than DNA to the next generation. With so many aspects to be accounted for, it becomes a challenge to link them all to the concept of evolution in a transparent way. As demonstrated in Figs. 16.2 and 16.3 the graph-pattern of Darwinian evolution contributes to this endeavour.

ERRATUM TO

Chapter 2
Introducing the Operator Theory

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G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_2

DOI 10.1007/978-3-319-43802-3_20

p. 44, Fig 2.3 – Figure source information was missed in the print and online version. Following source information was added in the end of figure caption in both print and online version.

'The corresponding author of this chapter has allowed A. Chatterjee to publish this figure in Chatterjee (2016, as figure 6), from which it is reproduced here with permission from Bentham'.

The below reference was not included in the previous version, however, it have been updated in this volume.

Chatterjee A (2016) Energy, Entropy and Complexity: Thermodynamic and information-theoretic perspectives on ageing. In: M. Kyriazis (2016) Challenging Ageing: The anti-senescence effects of Hormesis, Environmental Enrichment, and Information Exposure. Bentham.

The updated original online version for this chapter can be found under
DOI http://dx.doi.org/10.1007/978-3-319-43802-3_2

G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3_20

Appendix

G.A.J.M. Jagers op Akkerhuis (ed.), *Evolution and Transitions in Complexity*,
DOI 10.1007/978-3-319-43802-3

Table 1 Relationships between the major evolutionary transitions as proposed by Maynard Smith and Szathmáry (1995) and the Operator Theory as proposed by Jagers op Akkerhuis and van Straalen (1999)

Major transitions (original version) (1995)	Major transitions (version 2.0) (2015)	Operator Hierarchy (1999–2016) Kind of operator involved in the major transition	Operator Theory (2008–2016) Object of study is: –an operator –a compound obj. –a group	Operator Theory (2008–2016) Dimensions: –Upward dimension –Inward dimension –Outward dimension
Replicating molecules to populations of molecules in compartments	Proto-cell	From molecules to the construction of the cell	Operator (cell)	Upward dimension: Integration to the next level operator
Unlinked replicators to chromosomes	Genetic code and translation: prokaryotic cells	Change inside the cell, involving molecular operators	Operator (cell)	Inward dimension: Transition takes place inside a cell
RNA as gene and enzyme to DNA and protein	Genetic code and translation: prokaryotic cells	Change inside the cell, involving molecular operators	Operator (cell)	Inward dimension: Transition takes place inside a cell
Prokaryotes to eukaryotes	Eukaryotic cells	Construction of cell with endosymbiont (the operator kind is called the "endosymbiont cell")	Operator (endosymbiont cell)	Upward dimension: Integration to the next level operator
	Plastids	Entering of additional endosymbiont (the operator is still an "endosymbiont cell")	Operator (endosymbiont cell)	Upward dimension: Integration to the next level operator
		Multicellular (based on bacterial cells, e.g., Blue-green algae)	Operator (multicellular)	Upward dimension: Integration to the next level operator
Asexual clones to sexual populations			Group	Outward dimension: Change in interactive properties leads to a new kind of group

Protists to animals, plants and fungi	Multicellularity	Construction of the endosymbiont multicellular (fungi, algae, plants)	Operator (endosymbiont multicellular)	Upward dimension: Integration to the next level operator
		Construction of Neural network organism (multicellular animal or, in terms of the OT, a "memon")	Operator ("memon")	Upward dimension (while occurring inside a multicellular): Groups of neurons realize second order recurrent interactions with interface of sensors and create the next level operator
Solitary individuals to colonies	Eusocial animal societies		Group	Outward dimension: Change in interactive properties leads to a new kind of group
Primate societies to human societies	Societies with natural language		Group	Outward dimension: Change in interactive properties leads to a new kind of group

Shading in the *rightmost column* indicates the inward (*white*), upward (*grey*), and outward dimension (*dark grey*) of the OT

Authors Biographies

Henk Barendregt (1947) studied mathematical logic at Utrecht University, obtaining his Masters in 1968 (cum laude) and his Ph.D. in 1971 (cum laude) under Dirk van Dalen and Georg Kreisel. Between 1986 and 2015 he was a professor at Nijmegen University, The Netherlands, where he occupied the chair of Foundations of mathematics and computer science. He was rewarded the NWO Spinoza Award in 2002 and the Distinguished Lorentz Fellowship at the Netherlands Institute of Advanced Science in 2012.

Henk is known for his work in lambda-calculus and type-theory and has worked on Formal Mathematics, a field towards the machine verification of proofs occurring in mathematics and in reliable hardware and software development. In addition to mathematical logic, Henk is a practitioner and teacher of the insight meditation and has been studying consciousness, both theoretically and experimentally.

Atanu Chatterjee is currently a doctoral student of Physics at the Worcester Polytechnic Institute, USA. Atanu holds a Masters in Applied Mathematics (2015) and a Bachelor in Engineering (2013). He is interested in developing a formal theory to describe self-organization in nature and in the dynamics of complex networks. He is a member of the Evolution, Cognition and Complexity group at VUB, Brussels.

Georgi Georgiev has always been working on the questions of why and how complex systems self-organize, what are the parameters that interact to produce the engine of the exponential processes of self-organization leading to the current variety and projecting its future trajectory. According to him self-organization is the tendency to follow the natural motions of all objects as described by the Principle of Least Action, which leads to the dynamics of complex systems minimizing obstructive constraints.

He obtained his master's degrees in physics and chemistry from Sofia University, and another master's degree and a Ph.D. in Physics from Tufts University, in Boston, Massachusetts. He completed 3 years of a post-doc at the Center for Interdisciplinary Research on Complex Systems at Northeastern University, in Boston, Massachusetts.

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DOI 10.1007/978-3-319-43802-3

Currently he is doing research at the Worcester Polytechnic Institute and at Assumption College in Worcester, Massachusetts, USA.

Bart Gremmen focuses on ethical questions in relation to developments in plant and animal biotechnology, and animal welfare in livestock. A pragmatic philosophical approach is followed to ask normative and conceptual questions about how we treat animals and how we should relate to new biotechnologies. Questions, concerns, and arguments of stakeholders (farmers, scientists, citizens, etc.) are used as a basis for critical reflection.

Bart studied philosophy (cum laude) at the Radboud University and received his Ph.D. at the University of Twente. He has been the director of the centre for Methodical Ethics and Technology Assessment (META), a special professor of Ethical and Social Aspects of Genomics (2006) and of Ethics in Life Sciences (2011), and a personal professor (2016). He has been managing the societal program of the Centre for BioSystems Genomics (CBSG), and of the Celiac Disease Consortium (CDC). He is a senior research associate at the Oxford Uehiro Centre for Practical Ethics.

Gerard A.J.M. Jagers op Akkerhuis studies the past, present, and future of the universe and is driven by a passion for evolution and complexity. Gerard's work focuses on a modern, scientific version of the classical Scala Naturae named the Operator Hierarchy. This hierarchy offers a mechanistic basis for the classification of objects in the world, connects biotic and abiotic evolution, and by extrapolation suggests future system kinds in evolution. Since 2013 Gerard has been involved in the artificial intelligence company "Mind|Construct."

Gerard obtained his Masters in Wageningen (1986, cum laude), received his first Ph.D. in Ecotoxicology (Wageningen, 1993) and, 17 years later, his second Ph.D. in philosophy (Nijmegen, 2010). Gerard has (co-)authored over a hundred publications and has published two books: "The operator hierarchy" and "The pursuit of complexity." He has been interviewed by a national newspaper in the series about "Controversial thinkers whose ideas can change our view of the world."

Hans Peter Koelewijn, driven by an interest for understanding natural variation, focused on the importance of genetics for understanding population ecological processes. During his Ph.D. he became interested in genomic conflicts. At Alterra this bonded him with Gerard Jagers, since both were wondering: "What actually is the unit of selection?" This question touches upon the Operator Theory. By viewing operators, diversification and selection as the core aspects of evolution it became possible to extend the unit of selection beyond the field of biology.

Hans-Peter obtained his Masters from Utrecht University (1985, cum laude), and received his Ph.D. (Plant Mating System Evolution) also from Utrecht University (1993, cum laude). Thereafter, he studied Experimental Evolution in microbes, driven by his curiosity about adaptation to different environments. Next, he applied genetic methodology for nature conservation at Alterra. Currently he integrates results from Whole Genome (re)Sequencing efforts for application in plant breeding with Bayer Crop Sciences.

Thomas Reydon's interests focus on, among other things, the analysis of core concepts in biology; the foundations of classifications; the epistemology and metaphysics of natural kinds; the explanatory scope of evolutionary theory; and traditional themes in philosophy of science such as explanation, laws of nature, scientific realism, etc. He is also interested in metaphilosophical questions about the nature and goals of philosophy, and relationships between philosophy and other sciences.

Reydon obtained an M.Sc. degree in physics and an M.A. degree in philosophy of science, both from Leiden University. He obtained his Ph.D. in philosophy of biology with a dissertation written in the theoretical biology group at Leiden University's Institute of Biology. He has been a research fellow at the Center for Philosophy and Ethics of Science (ZEWW) at Leibniz Universität Hannover. Since 2015 he is professor of philosophy of biology at the Institute of Philosophy, Leibniz Universität Hannover. He is an associate editor of the journal Acta Biotheoretica and one of three editors in chief of the Springer book series History, Philosophy and Theory of the Life Sciences.

Michael Russell's research focuses on the emergence of life and oxygenic photosynthesis in the context of hydrothermal systems on wet, rocky, sunlit planets. His work has a strong focus on nonequilibrium thermodynamics.

Russell studied Geology with Chemistry at the University of London (B.Sc. Honours, 1963), and obtained his Ph.D. on Mineral Deposit Geochemistry, University of Durham (1974). Since that time he has had a long series of professions including for example party chief at Falconbridge Nickel Mines (Canada), departmental chair and professor at the applied geology department of Strathclyde University, professor of applied geology, Glasgow University (Scotland), CNRS professor, University of Grenoble (France), research scientist V, JPL/California Institute of Technology (USA), and supervisor, planetary chemistry and astrobiology group at the jet propulsion lab of NASA (2013 - Present). He was awarded the 2009 William Smith Medal, by the Geological Society of London for contributions to applied geology.

Hendrik Pieter Spijkerboer (Diedert)'s lifelong passion for knowledge and learning has led him to spend most of his career so far in two major fields. One field is science, including plant disease epidemiology, ecology, and evolution theory. The other field is education, with a special interest in the development of tests for students.

Diedert received a M.Sc. in Environmental Physics from Wageningen University in 1995 and a Ph.D. in Production Ecology from Wageningen UR in 2004. His current work focuses on better understanding the concept of evolution, through a philosophical interpretation of the general requirements for any model of this phenomenon.

J.W. (Jan-Willem) Stoelhorst is an Associate Professor of Strategy and Organization at the Amsterdam Business School, University of Amsterdam. His principle research interest is the application of evolutionary theory in the social sciences, in general, and in economics and management studies, in particular. He is research area coordinator for "The ontological foundations of evolutionary economics” at the European Association for Evolutionary Political Economy. In addition to his work on strategy and organization, he has published on both the generalization of evolutionary theory (under the label “generalized Darwinism”) and on its application in evolutionary economics and to the theory of the firm (under the label “naturalistic theory”).

Nico van Straalen is interested in the application of molecular insights to problems of ecology and evolution, e.g., natural selection, adaptive change, transcriptional regulation in evolutionary processes. He has a keen interest in stress due to environmental pollution, because pollution is often a strong selection pressure that can be quantified and experimentally manipulated supporting the investigation of evolutionary processes.

Since 1992 van Straalen is a full professor of Animal Ecology, Vrije Universiteit. He has been the dean of the Amsterdam Graduate School of Life Sciences (2011–2012) and is a member of the faculty board since 2015, responsible for education. He has been the promotor of more than 60 Ph.D. students, and is the (co-)author of over 300 scientific publications, and the author of the following books: “Leerboek Oecotoxicologie” and “An Introduction to Ecological Genomics”.

Jack Vromen’s main research area is Philosophy of economics, with an emphasis on conceptual and meta-theoretical aspects of the relation between evolutionary and economic theorizing.

Vromen (1958) is a professor of Economics and of Theoretical Philosophy, with a special emphasis on Philosophy of Economics. Jack Vromen obtained his Ph.D. degree (cum laude) in Economics at the University of Amsterdam in 1994. Currently he is dean of the Faculty of Philosophy and Academic Director of the Erasmus Institute for Philosophy and Economics (EIPE) at Erasmus University Rotterdam.

Hub Zwart (1960) studied Philosophy and Psychology at RU Nijmegen (NL), defended his thesis in 1993 and became a full Professor of Philosophy at the Faculty of Science (RU Nijmegen) in 2000. He established and directs the Centre for Society and Genomics and the Institute for Science, Innovation and Society (ISIS) and is involved in several European projects. His research focus is on the philosophical dimensions of emerging life sciences, notably genomics, synthetic biology, and neuroscience. Notably, he is interested in how the life sciences challenge and affect our understanding of life and nature as well as of ourselves as human beings.

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DOI 10.1007/978-3-319-43802-3