COMPLEXITY

OF THE BIG AND SMALL

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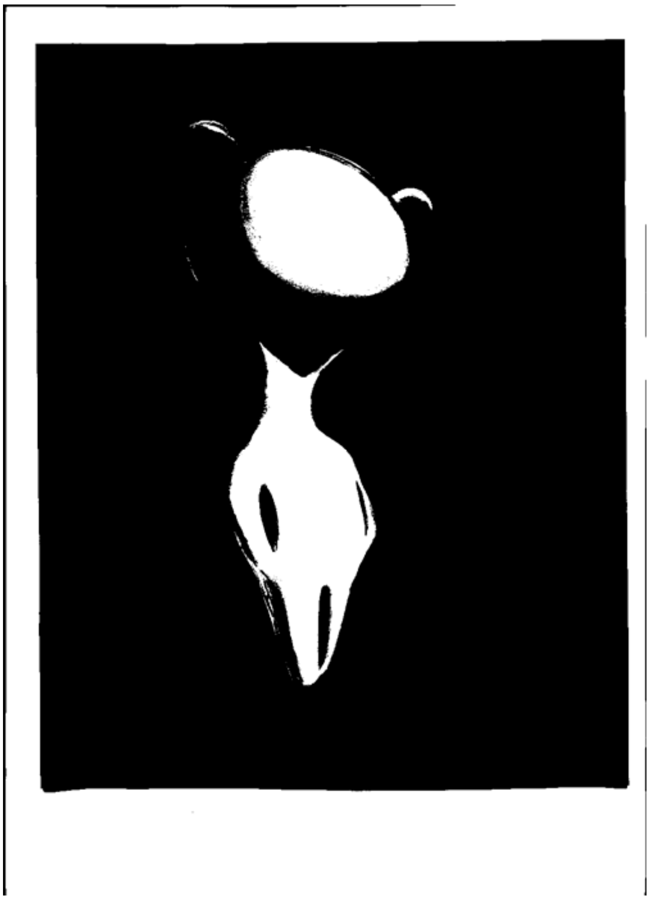

Complexity daemon

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or part been submitted at any other university for a degree.

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ABSTRACT

It seems to be a priori impossible to formulate any general theory or model that encompasses all of the properties of complexity. So, one must make do with partial solutions. A possible approach we propose is to take inspiration from quantum theory, since there seems to be a *strong analogy between complex systems and quantum systems*. Although we do not propose any literal application of quantum mechanical formalism to complexity, we suggest that the language of quantum mechanics is already so well developed - and for a much wider spectrum of problems than most theories - that it can serve as a model for complexity theory. There are many problems common to both complex systems and quantum systems and we suggest that it might be useful to test the applicability of aspects of the "language" of quantum mechanics to a general complex system. What we suggest here is an *interdisciplinary* talk led between the natural sciences and philosophy, which we believe is the only way in which to deal with complexity "as such".

ABSTRAK

Dit wil voorkom asof dit a priori onmoontlik is om ‘n algemene teorie of model te formuleer wat al die aspekte van Kompleksiteitsteorie insluit. Mens moet dus tevrede wees met gedeeltelike oplossings. Hierdie werk hou een moontlike benadering tot kompleksiteit, wat sy inspirasie uit die kwantumteorie neem, voor, omdat *daar ’n beduidende ooreenkoms tussen komplekse en kwantumsisteme bestaan*. Alhoewel ons, ons nie daarvoor beywer dat kwantummeganiese formalisme direk op komplekse sisteme toegepas word nie, dui ons aan hoe goed ontwikkel die taal van die kwantummeganika reeds is en hoe dit ‘n wye spektrum van probleme dek. As gevolg hiervan, en as gevolg van die ooreenkomste in probleemstellinge rakende komplekse en kwantumsisteme, voer ons aan dat die kwantumteorie as ‘n model kan dien vir kompleksiteitsteorie. Ons poog dan ook om die toepassingsmoontlikhede van ‘n deel van kwantumteorie op ‘n algemene komplekse sisteem te toets. Wat ons hier voorhou is ‘n interdissiplinêre gesprek tussen die natuurwetenskappe en die filosofie, omdat ons glo dat dit die enigste nuttige benadering tot kompleksiteit is.

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FOREWORD

This work has been developed in the course of three years after my visit of the University of Stellenbosch, South Africa, in 2001. At the beginning there was a series of kind discussions with Professor Paul Cilliers from the Department of Philosophy, which lead to the recognition that we shared almost the same interest of issues standing on the border between philosophy and natural sciences. We both, although originally educated in physics, after a few years fell for the beauty of a philosophy that is – whether you want it to be or not – strongly interconnected with what we call the 'exact' sciences.

We chose the topic of 'complexity', which interested both of us. And while Prof. Cilliers has already been working on this issue for a long time – and still does today – these problems were completely new for me. Up to that time I had mainly been dealing with the methodology of science in general, and specifically with sc. interpretations of quantum mechanics. (In 1999 I defended my Ph.D. theses, with the title "Quantum mechanics from the viewpoint of classical realism", at the Charles University in Prague, Czech Republic.) After a short time, however, I found that the sets of problems and questions of quantum physics and complexity overleaped much more than I would ever have expected.

It endowed me with a great optimism. The topic we had chosen was not so "endless" as it had seemed, but suddenly appeared to be quite familiar and promised to be manageable somehow. Nevertheless, one thing was inevitable: it required hard interdisciplinary work, which always presents great difficulties in itself.

Interdisciplinary work is not easy for many reasons: It places demands on both the authors and their readers for knowledge of different issues. In the case of our work, a significant knowledge of both philosophy and physics is needed. Moreover, in the course of our treatise, we also touch upon many topics from biology, chemistry, linguistics, informatics, etc. It is clear then that none of these issues can be elaborated on as deeply as by a specialist. But, that is not our intention, anyway. Rather, we want to give an overview of the most fundamental questions of all these scientific fields and to outline possible answers.

This aim, however, raises one negative consequence: many readers specialize in some particular problems will probably find many inaccuracies in our work. We are well aware of this fact and therefore we kindly ask these people for generosity – especially when it comes to the “weak points” of defining and using particular terms. The overview of works dealing with particular problems is orientational rather than exhaustive.

To reduce the inaccuracies in our physics we asked for help and supervision from Professor Hendrik Geyer, from the Institute of Physics at the University of Stellenbosch, to whom we address our kindest acknowledgement. My ex-husband, Dr. Pavel Cejnar from the Faculty of Mathematics and Physics, Charles University in Prague, was also consulted on sections devoted to quantum mechanics and I would like to say thank you to him as well. And not least I would like to acknowledge Dr. Libor Juha from the Institute of Physics, at the Prague Academy of Sciences, for his great help with searching for the required literature.

I read most of the literature as listed at the end of this work in English, but some books or papers I could only find in the Czech translations. In these particular cases and in the cases where I quoted them only as secondary sources I do not state the page in the quotation bracket in the text.

I hope that you will enjoy reading our paper and that it will give you some inspiration as to how it might be possible to look at complexity, and implicitly at the whole world that surrounds us – since, as the subtitle of the Introduction chapter says, the entire world is complex.

Andrea Cejnarova
Prague, January, 18 2004

I INTRODUCTION

/The entire world is complex/

Complexity is a basic feature of the world. This is a simple statement but very difficult to understand. Why? Because nobody fully understands what the term ‘complexity’ actually means. According to our common sense we would say that ‘complex’ is a scientific name for ‘very complicated’. This is true to some extent. But what does ‘complicated’ mean, exactly? Complicated can refer to a problem which we cannot solve, because we do not know where to start - it requires more computing power than we have, or we are involved in it personally and emotionally, which prevents us from “impartially” looking for a solution. ‘Complicated’ can refer to a person or a machine; needless to say, both in a different sense. Many things can be complicated; one could say that all things that are not evaluated as ‘simple’ are actually complicated.

Here one should stress the inherent *subjectivity* that is the cornerstone of all decisions on what is ‘complicated’ and what is ‘simple’. This categorization will certainly differ from person to person for it is subject to personal faculties, knowledge endowment, emotional involvement, etc.

This example declares the well-known fact that one sometimes does not have a choice other than to use words without the possibility of grasping their full meaning in each moment. In most situations it is enough to understand words “approximately” or to employ intuition and to guess at their right meaning. But, since we have chosen the phenomenon called *complexity* as the topic of our treatise, we must try to understand it as much as possible. From this point of view it would seem natural to start from the list of definitions of complexity one can find in literature. We mention some of them in Chapter II.

Though complexity comprises almost everything we see around us – we will try to support this statement with the help of two illustrating examples: the changing of seasons and the laws of human society – it is very difficult to define. Actually, no definition or list of definitions can describe it in a comprehensive way. It is the same as wanting to understand the world in its entirety. At the end of the opening part of Chapter II we even conclude that it is a priori impossible to formulate any general theory or a model encompassing all the properties of complexity. This is, however, nothing new or surprising. The same conclusion has been reached by many before us and it is also implied in the fact that there is a plurality of sciences, for instance. If this were not the case, we would cope with our world (at least the physical world) using the only one scientific (or non-scientific) approach. Nevertheless, the true situation appears to be the opposite: reality *must* be (and in practice always is) approached from different angles. This statement will be illustrated using a simple story of a tree growing close to people's houses and hindering them.

So, we dare to assert that *the real world is made up of complex things*. We say 'real' to stress that we are going to deal with real things, i.e. things that exist "independently of our consciousness". Here we opt for classical realism in its Aristotelian form, answering the question "Does the Moon exist even when nobody observes it" with a YES. And we are going to continue in this philosophical direction, based on Aristotle and on scholasticism, in Chapter II.

We adopted the particular teaching of these philosophers, because it harmonizes with our own thoughts and we find it complete, self-consistent and generally applicable to the questions at hand. Probably, at this point, not everybody will agree with us and we admit that this topic deserves much greater attention and deeper discussion concerning other philosophical trends (especially modern ones). Such a task would, however, require a special study that is beyond the capability of this work. In spite of this fact we are convinced that adopting a particular theory is a justified in a case such as this one, where the theory itself is *not* the main subject of the study.

An excursion into the classical theory of substance and accidents will help us to find out what complexity "as such" is. It can again be disputed whether or not this tool is the "proper" one for this study. Whatever is the right answer, this approach leads to a reasonable conclusion and that is not to be scoffed at, considering the exceptionalness and trickiness of the subject.

In the course of the text we will show that complexity can be categorised as a predicate of substance and that its character is accidental. We will call it "a quantity without any absolute value", since it reveals itself differently according to the distance from which one observes the system and the method one follows, with no definite preference of any of these two.

Does this mean that all possible knowledge of complexity can only be relative? This is an important question we will mainly deal with in the Chapter V. For now it is enough to abide with the assurance that complexity is knowable, since it possesses some kind of true existence and enters into non-trivial interactions with us as observers (although this far from being an evident and simple fact).

In the next section of Chapter II we will try to say more about nature of complex systems. We will find out that all complex systems are open, natural systems evolving in time. Moreover, a complex system presupposes the existence of structures with variations. These claims will be demonstrated using some everyday examples.

When we say that complex systems are "open" we mean that they continually undergo changes caused by their environment. They are inevitable parts of the non-trivial interactions that are characteristic for them. Even the simplest things we see around us are complex in some way because they never exist by themselves, but always enter into non-trivial relations with their surroundings and, what is more, with the observer. These last words then brings us again to the problem of knowing complex systems, mainly discussed in Chapter V.

Since deciding what is complex and what is not is such a tricky task, we have decided not to select aspects of the world according to the extent of their intricacy as some authors do. We would rather choose the more difficult path, paved with the conviction that *the world of simple mechanisms is a fictitious world*, and to deal with all things as being "living" members of the one Whole.

As we shell see later, "cutting" nature up into simple pieces is only a tool (albeit a powerful one) that enables us to comprehend complex systems to a reasonable extent. For this reason we prefer to see all natural systems as complex, although possibly in fundamentally different ways. What these "ways" are will be clarified in the section devoted to different modes of complexity.

In Chapter III we will deal with the questions of *where* complexity occurs and *how* it originates. With regard to the former question we will discuss the thesis that complexity emerges between chaos (read extreme disorder) and order. This is the area where structures originate. Structures are intricately intertwined with complexity as it is shown in Chapter II. This thesis has not come from anywhere specific, but is supported by much evidence and also corresponds with our intuition. The states of absolute order on the one hand and absolute disorder on the other hand represent only small domains at the opposite ends of the world-ordering-scale. Almost all of the world that we experience and live in finds itself between these two limits and – in correspondence with the thesis – demonstrates features of complexity.

To understand *how* complexity originates is a great challenge for all complexity researchers. It is clear that this is a rather general question touching the very basis of the world's functioning. It can be approached both from the side of general considerations of "how more complicated things originate from the complicated things" and from the side of individual scientific branches that deal with particular problems – e.g. in biology one can follow the line: DNA – cell organs – individual cells – body tissues – organs – systems of organs – whole living organism – society – biosphere, etc. Certainly, the chosen approach to this problem will differ significantly in both cases. The former will probably lead to philosophical discussions, and the latter to attempts to solve particular problems.

So, what are the mechanisms for creating complexity? This is the main question we will try to answer in Chapter III. It is clear that no definite and correct answer to this question exists. There can be two reasons for this: either the mechanism is so "special" that we have not recognized its exceptionality, or there is a plurality of such mechanisms without any preferences. Regardless of what is true, many theories – as candidates for explaining this mechanism – have been formulated. We will try to sketch out some of them for our readers.

The first one, which very promising, is the theory of *self-organised criticality* (SOC), formulated by Per Bak. According to this theory large dynamical systems naturally evolve (self-organise) into a highly interactive, critical state where a minor perturbation may lead to avalanches of all sizes. Thus, P. Bak evidently focuses on non-linearity and time-evolution as the two main features of complexity. This theory has been successfully applied to many phenomena observed in nature and it seems that its potential is even greater.

It is observed that complex systems usually do not evolve randomly but tend to converge toward some particular states, trajectories, shapes, etc. One of the hypotheses explaining this reality is the theory of *anti-chaos*, formulated by Kauffman. Kauffman understands things slightly differently from Bak, but his opinions are also quite interesting and well probable.

Another group of complexity researchers are keen proponents of quantum theory. They believe that it is the probabilistic nature of quantum mechanics that is responsible for the existence of complexity. It is true that one can find many common features between quantum systems and complex systems – one of the main theses of our work. However, it is also true that in this manner one can "explain" almost anything. The mystery of non-definiteness hidden in quantum theory has already enchanted many people and not always in a good way.

A different "area" of the world – taking size as a consideration – is explored by people who attempt to find some organising principle that causes the emergence of highly organised complex systems at the mesoscopic scale. This principle has not yet been discovered, but its existence is very possible. There is actually very little known about the mesoscopic field, since it is too small for direct observations, but too big to be counted.

The four theories mentioned above are just a few examples of the many that exist. They have only been chosen to show that the question "How does complexity originate" is still open, and that one cannot exclude the possibility that it will never be answered.

Now that we are understand complexity a bit better we can dare to look around us once again and to search out places where complexity occurs; and to specify them somewhat. It is without a doubt the case that our overview will not be complete and that all the systems that we will mention are not “complex” in the same way.

The first area that we will explore is the microscopic world, and we will pay the greatest attention to it. The reason is simple: we need a more detailed study of behaviour in microworld for considerations raised later in the text.

We will start this section with the rather way-out statement that there are many common features shared both by microscopic and complex systems. We will elaborate on this opinion with many examples taken from quantum theory. For the moment we can only sketch a few ideas: quantum systems possess hierarchical structure, they enter into non-trivial relationships, one cannot sharply determine their boundaries, they find themselves – when not being observed – in undetermined/fuzzy states, there is something called superposition acting on them, quantum systems change their states when evolving in time, and studying creates difficulties. Put in such terms it sounds imprecise and naive. In section 1 of Chapter IV we give a deeper analysis of these claims and we hope to convince our readers that the statement about the similarity of quantum and complex systems is well founded.

The second area we will visit on our journey through complexity is the domain of chemistry, which logically follows subatomic and atomic physics. Here we must stop to discuss a great personality of the scientific world – Alan Turing. Turing, for his part, was deeply interested in the chemical nature of formations of shape, structure and function in living beings (read: complex things). His studies are very interesting and of great importance for the whole of science. His results, however, also support one piece of evidence that is especially interesting for us: non-trivial structures also emerge at this level. The occurrence of such structures or patterns was confirmed by two Russian chemists: B. P. Belousov and A. Zhabotinsky.

To keep to the path we have chosen, our next steps will bring us to the kingdom of biology. To be alive is almost a synonym for being complex (though this is NOT a one-to-one correspondence). It is not necessary, in our opinion, to spend much time in arguing this point. They ARE complex and, what is more, both in their structure and in their function. However, in order not to abandon this topic so abruptly, we will give a short exposition on formation of structures in biology.

In as much as complexity is inherently intertwined with living, it is kept out of artificial materials and machines (as is also argued in Chapter II.) Though we still hold the position that complex things are *natural* things, we must admit that this fact is far from being self-evident. And it still gets “worse” as the scientific “process” proceeds. Particularly when it comes to intelligent materials and non-trivial machines (It was Heinz von Foerster who, in terms of Alain Turing, first started to distinguish between trivial and non-trivial machines.) To talk about intelligence in connection with materials is unusual, to say the least. This term has become common, however, although the connection is rather metaphorical.

The last area we will discuss is language. Language is another “tricky” representative of complex systems. Why tricky? Because language evidently IS a complex system, but one hesitates to classify it as a natural or an artificial system. The existence of verbal language is bound with humankind. However, it belongs to humankind in a different way than the human brain, for example. Language is not a “thing” but a “skill” and as such it can be understood as an artificial entity. But, this is not completely satisfying. The element of *consciousness* is missing here. Natural languages are not the products of conscious efforts, nor are they taught – as native languages –in the same way as crafts, for example. Moreover it appears that our knowledge of language is much larger than our experience, i.e. the sources or materials one could use for creating language (see the passage devoted to Professor Boskovic). Nevertheless, language surely IS one of the most important representatives of complex systems so it cannot be excluded from our thesis.

We complete Chapter IV with a section devoted to another very interesting feature of complex systems, i.e. their tendency to enhance their inherent complexity. It is observed that the operations of complex systems tend to develop more complexity. Thus, complexity in nature is still increasing. Is this fact somehow explicable? Many scientists are convinced that it is, and they have proposed four principal modes of this process. (We will sketch them briefly in our text.) Although they differ from one another significantly, they agree that the self-enhancement of complexity is an evident fact that has far reaching consequences – mainly because it provides room for natural evolution and development.

Usually the adjective ‘complex’ or ‘complicated’ is associated with the attribute ‘big’. But, this is rather misleading as we show in Chapter IV. Small things, particularly microscopic systems, are complex in a very similar way as systems of big things, e.g. a huge group of people. Moreover, even non-material things are complex, e.g. human language. That is why we conclude that complexity is more a function of system qualities than size. Therefore it is not without merit to speak of complexity as occurring from the subatomic level up. This is a very important conclusion, because it allows us to build *a coherent picture of the world (complexity)* without any need to put up borders between different systems or groups of systems.

And indeed, in the course of our work we will visit many different scientific branches dealing with different subjects. Even though our overview will only be done briefly (any deeper insight would be beyond the potential of this paper) we hope it will fulfil our intention to declare that if one wants to reach complexity he or she can start their investigation almost *anywhere* they want to. The starting point for complexity studies is arbitrary, for complexity really is everywhere.

The “true complexity” of real objects is very difficult to study and to describe. It is, and probably will always be, totally beyond us. There are many reasons supporting this conclusion. The main reason consists in the fact that we never interact (observe) with the whole systems, but only with certain of their aspects at a particular time. It is similar to problems of observing objects that are too big or too far away or too small. The family of the “problematic” sciences of the big and small, e.g. astrophysics and quantum mechanics, should branch out into a new member: the science of complexity, i.e. the science of very complicated systems. The reason is that another aspect of all natural systems has been “rediscovered”, in that it was well known to humankind since the very beginning of its cognitive aspirations, but which was treated as ungraspable by sciences, and thus “uninteresting” – their complexity.

Is it really so that complexity is totally "ungraspable by science"? In Chapter V of our treatise we will try to give an answer to this question. Interest will be paid to the problem of how to measure or control complexity. As we already indicated, capturing complexity is a very tough problem. First of all, complexity shows itself from two sides - as cognitive and ontological complexity. In short: complex systems are 'complex' by themselves and it is also a complex problem to know them. It is possible to give a philosophical picture of both of these modes, but to grasp them rigorously is an *a priori* impossibility.

One of the main reasons for this is as follows: it is very hard to distinguish between an observer and the observed system. In this situation both of them are complex; they influence one another and they undergo changes during the process of observation. As a consequence, many theorists have concluded that complexity makes sense only when considered as relative to a given observer. Analogical discussions have been prevalent in astronomy, for example, where the inability to make direct observations raised questions as follows: "What do we really observe via the telescope?" or "What is the reality-status of distant stars when the light needs thousands of years to reach us?" An even more similar situation can be found in quantum mechanics where the statement "It only makes sense to speak about a quantum system when someone observes it" was embedded into the very foundations of the theory.

One of the possible ways out of these difficulties would be to assign them to our limitations as human beings, and to accept that computers could overcome them. This idea looks very promising and many people strongly believe in it. However, it also has its 'limits'. Practical limits – i.e. our deficiency in counting and absorbing a huge number of information quickly, etc. – can definitely be overcome now-a-days by computers. Nevertheless, there are also theoretical limits – prescribed by a theory – that are almost fixed and probably will keep us from an exhaustive knowledge of complexity forever. (For further discussion see Chapter V.)

Although the situation does not look promising, a lot has already been done on the way towards a better understanding of complexity. It is clear that the main body of work has been done using modern computers the abilities of which had been undreamt of until recently. In our paper we will mention some of the revolutionary outcomes relating to cellular automata, neural networks, artificial intelligence, etc.

After some study of these problems one can easily come to recognise that in the same way that the whole of science is divided into different branches that deal with different questions, complexity studies are divided into different subdivisions that complexity from different viewpoints. Thus, the natural question is: is there any unified theory of complexity that would give a coherent picture of it? Or, at least, can we hope that it will be found someday? The answer, unfortunately, seems to be negative. The theory of everything is still far beyond our horizons if it is even possible.

In the course of this chapter we have already stressed that we see a *strong analogy between complex systems and quantum systems*. We have supported this statement with the help of many examples. Now, it is time to take a step forward and to explain why we stress this analogy and what this can bring to us.

We see quantum mechanics (under 'quantum mechanics' we also include all related disciplines, i.e. quantum field theory, relativistic QM, etc.) as an extensively elaborated theory – mainly from the point of view of mathematical formalism. Its creators have not hesitated to set aside well-defined tasks and to get down to solving general problems concerning the time-dependent functioning of the whole (micro)world.

One of the answers that they looked for was how classical reality emerges from the "soup" of quantum objects and they created some very interesting theories. Undetermined complexity can also be seen as a "soup" but the world we live in is quite defined. So, why not try to borrow a theory from quantum mechanics that deals with this problem? Here we speak, of course, of the theory of decoherence.

In short, the ideal quantum state of superposition is regarded as coherent and therefore classical states; when superposition is not observed states are considered as *de*-coherent. The authors of the theory of decoherence (W. Zurek et al.) explain this as follows: quantum mechanics "works" for objects of all sizes, but the big ones cannot be isolated from their surroundings to prevent *decoherence*. On the other hand, quantum objects can be seen as quite well isolated, so they can posses and show their quantum behaviour.

Let’s consider an atom. In the middle there is a nucleus composed of protons and neutrons and there are electrons circulating around the nucleus at a great distance – relative to the measurements of the nucleus and electrons. Though, they are mutually tied together by electromagnetic forces, there is actually a huge “empty” space between the nucleus and electron orbits. Similarly, most of the quantum world is a wide, almost empty space. Conversely our “classical” world is quite densely inhabited. Compared to sizes of macro-objects their mutual distances are quite short. That’s why we have the problem with isolation.

The complex world is even more different. Although we do not want to get stuck in a simple holism, we can hardly say where one complex system begins and where it ends. One is part of another that is part of another ... continuing ad infinitum. If we see the universe as one huge complex system then one could suppose that it provides no conditions for decoherence as well. We do not mean to say that we expect exactly the same quantum states such as superposition, for example, at the level of such a “meta-complex-Universe”, but perhaps something similar. Actually, the only thing we want to state is that in the same way that quantum reality significantly differs from the reality of the classical domain, complex reality differs from the classical one. As if we would approach “our” world once from below and once from above. Whereas the question of “how classical reality emerges from the quantum substrate” is of great scientific interest, the question of “how classical reality emerges from the complex substrate” is generally ignored – with some exceptions. So, why not to take inspiration from quantum mechanics?

The same goes for the problem of observation in quantum mechanics and theories of complexity. Regarding the former one we mentioned the Many Worlds Theory (MWT) proposed by H. Everett, and the Theory of decohering histories. Both of them – although some might think it ridiculous – provide a space for well-based discussions about the reduction of quantum/complex states caused by the act of observation.

One of the most famous paradoxes of quantum mechanics is the sc. collapse of wave function. Every quantum object undergoes a sudden, jump-like change right at the moment when it is observed. It changes its state. The same happens when a complex system is observed. From all of the possible states characterised by the countless numbers of complex variables only one particular realises itself – the one we actually see. What are the mechanisms of this process? Proponents of MWT theory would suggest that one system "lives" different lives in different worlds and we – as observers – can take a look inside just one particular world. Or, one can consider the system as possessing different histories that decohere into one particular history. Here the analogy is even more apt.

Though, many people would probably find such transfers of simplified extracts of rigorous physical theories unacceptable, we offer it at least as inspiration for how to think about complexity. We stress again that we do not propose any literal application of quantum mechanical formalism to complexity. We only want to point out that the language of quantum mechanics is already so well developed for such a wide spectrum of problems – as is hardly any other – that it can serve as a kind of model for complexity studies.

The common problem that touches both quantum and complex systems is the problem of *reductionism*. In the case of complexity it is the *reduction* of more complicated things to simple ones. This question, fundamental to the methodology of science in general has troubled people since the very beginning of their scientific efforts. The more complex the problems we deal with the more urgent this question. Therefore, we cannot avoid it – on the contrary we must pay significant attention to it. We will devote most of the Chapter VI to this issue.

In the course of the work on complexity we have vindicated to ourselves that the statement claiming that one can approach complexity from an arbitrary site is accurate. Whatever topic we chose we always finished with almost the same results. Although we should have expected it, we were surprised at the same time by its urgency. We are convinced that our readers will get a similar impression when reading the following text. It brought us to a quite daring attempt to try to bring together things as different – at least at first glance – as general complexity and quantum mechanics.

Actually we realised that there are many common problems touching complex and quantum systems[1] that allow us to presuppose that it should be useful to test the applicability of a part of the developed “language” of quantum mechanics to a general complex system. If it is possible, it would provide us a useful tool for work with complex systems and it would help us to learn more about them. Whether we succeed or whether it comes to nothing is dealt with in the last chapter (Chapter VII).

It is obvious that especially this chapter will cause many disagreement and even irritation among its readers. Despite this fact we still believe that such experiments do have some importance. At least they are promising to uncover new common features that can be generalised or could provide us with new ideas on how to grasp a given problem. It is the only intention we have: to place complexity into a new light.

Undoubtedly, everybody who wants to extract any scientific (even philosophical etc.) knowledge about the Universe must focus on the right level of description and reduce things. What methods one can use and what conclusions one dares to formulate is the subject of debate. The best chance to address this problem is *interdisciplinary* talk led between the natural sciences[2] and philosophy. And this is what we are going to do. To bring different scientific branches together with philosophy and, what we call, common sense.

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[1] Strictly speaking complexity is one attribute of a quantum system as well as of the wholeness the quantum system is part of.

[2] We put stress on “undivided” due to our conviction that here should be only one coherent scientific picture of the Universe as opposite to the tendencies of today to divide individual scientific branches into the more and more narrow disciplines.

II THE SPIRIT OF COMPLEXITY

When I write these words it is just beginning of summer in the central Europe and the whole of nature is at the height of its bloom. As with every year, the summer days were preceded by a long European winter when almost everything slept to collect the energy to begin a new season of growth. Newcomer spring has brought forth new life-activities. Trees received green coats again and started blooming to have fruit later. Many new plants germinated to replace the old ones and the rest woke up to continue in the growing that had been interrupted for several months. This change was also experienced by animals. Some of them even slept through the winter; some of them only reduced their activities and waited for spring to have enough food and warmth to be able to raise offspring. The average temperature started to increase as well as the amount of daylight. And, after the culmination in summer it will slowly return to a state of long nights, cold days and snow cover. Trees will lose their leaves again and the whole of nature will fall asleep again, until the next spring.

This is the well-known cycle of seasons as everybody in our European latitude has experienced since birth. We accept it as an obvious reality; we do not think about it and it cannot surprise us. These regular changes are so deeply rooted in us that we automatically assume that they will arrive as usual – at the right time. When they don’t, we are taken by surprise unconsciously blurting: “This year autumn came too early” or “This winter is already lasting too long.” But, what would we say if the winter lasted forever and spring never came? We cannot even imagine that.

So, from experience we can predict – with more or less accuracy – what the particular season should look like. But, every season is composed of individual days that follow one another. The transition between seasons is smooth, almost invisible. We do not experience any sudden "jump" from winter to spring for instance. It is a continuous process forming a closed circle; a little different from year to year. Moreover, each of these days is characterized by the particular weather, which snaps more or less into the seasonal frame but which is by itself a very complicated thing. It is even possible to say that it is so complicated that up to now nobody has understood its mechanisms fully.

The cause of this is the sc. butterfly effect; where the stroke of a butterfly's wing above the American continent can cause a hurricane in Japan, for instance. In fact, this is a great exaggeration; however, it is true that every – even the smallest – change in local weather rapidly multiplies and manifests itself on the global scale with an effect that is umpteen times stronger. This resulting effect is almost unpredictable from the initial conditions that cause it. Phenomena with such developmental kinetics are called non-linear, because the effect dependence on the initial conditions is not linear, but exponential.

Another interesting aspect of this situation is that the rather incidental behaviour of a system does not result in a final chaos, but rather in a kind of order; An order that is due to other influences coming from "above". In this particular case it is the mutual positions of the earth and the sun that are responsible for keeping order in the changing seasons. On the other hand, disorder in the local weather is caused by the particular conditions of the Earth's atmosphere. Both these systems are somehow correlated and intertwined in non-trivial ways, influencing one another in both directions. When there are many sunny days in winter, the winter is appreciated as "unusually warm". Nevertheless, because it is winter, it is not possible for the day temperature in the Czech Republic to be more than, let us to say, 15 °C. All of this together constitutes a complex system.

Weather forecasts represent the first use of computers for the modelling of complex systems. The first groundbreaker of these efforts was Lorenz who in 1960 succeeded on his device, called Royal McBee, to create his first weather imitation. Needless to say that it was very simplified.

Nevertheless, it started a whole new scientific branch, one that has experienced a great boom in recent years.

Another great example of complexity that we experience first hand is a human society. When we live in Europe we can take its geo-political and economical structure. This is not possible without mentioning the European Union (EU) which houses most European states, routing their political and economical development to some extent. Although it is a kind of authority that reduces their degree of freedom, it does not inhibit the individual states from developing. Besides the EU there are other barriers to individual states' activities, namely their own governments elected by their own inhabitants. Further down in this succession are the regional governments, then the political parties etc.

Going down the list we finally get to the individual people, to every single person. From the point of view of the EU one Mr. Novak[3] living in Prague is completely uninteresting. However, many "Mr. Novaks" create the Czech Republic, and their political orientation and labour productivity is already crucial for the EU. Since we know the activities of the EU we can successfully guess at what our country will look like after joining the EU,[4] but can we guess how Mr. Novak will behave in the future? Absolutely not. There are so many factors that enter into his life that do not allow us to make any predictions. The only thing we know for sure is that if he does not behave according to EU laws he will end up in prison.

These are two examples of big complex systems, illustrating that the term complexity comprises almost everything we see around us. So, what in actual fact can we say about complexity that is concrete? Although people's knowledge of complexity, thanks to the sciences, is quite extensive, it is still difficult to define it. New definitions are added to the list but we are still not able to say *what complexity really is*. For example at least 31 definitions of complexity were proposed in a list compiled several years ago by Seth Loyd of the Massachusetts Institute of Technology. J. Horgan re-introduced some of them according to their keywords as follows (Horgan 1995: 74):

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[3] 'Novak' is one of the most common Czech names.

[4] Czech Republic is going to join EU fully in May 2004.

- **Entropy:** Complexity equals the entropy, or disorder, of a system, as measured by thermodynamics.
- **Information:** Complexity equals the capacity of a system to “surprise”, or inform an observer.
- **Fractal dimensions:** The “fuzziness” of a system, the degree of detail it displays at smaller and smaller scales.
- **Hierarchical complexity:** The diversity displayed by the different levels of a hierarchically structured system.
- **Grammatical complexity:** The degree of universality of the language required to describe a system.
- **Thermodynamic depth:** The amount of thermodynamic resources required to put a system together from scratch.
- **Time computational complexity:** The time required for a computer to describe a system (or solve a problem).
- **Spatial computational complexity:** The amount of computer memory required to describe a system.
- **Mutual information:** The degree to which one part of a system contains information on, or resembles, other parts.

It is not our aim to deal with these definitions in detail at this moment. Anyway some of them will again appear in this text when we touch upon the particular problem. For now we want to give an impression of their variety. Obviously they were formulated from different points of departure, all of them are valid and none of them is better than the others. In like manner D. C. Mikulecky says (Mikulecky: http.):

> *Complexity is the property of a real world system that is manifest in the inability of any one formalism being adequate to capture all its properties. It requires that we find distinctly different ways of interacting with systems. Distinctly different in the sense that when we make successful models, the formal systems needed to describe each aspect are NOT derivable from each other.*

Let’s consider a tree growing between blocks of flats in a busy town. It is high and spreading and many people argue that it should be cut down because it casts a shadow at windows of the neighbouring houses. For this reason inhabitants of the affected buildings call a meeting to the public hall. Moreover, they call for a study showing the tree’s effect on the illumination of the chosen flats. In this study the living tree is represented by a physical object acting as an obstacle situated between the source of light – i.e. the sun – and the place where the light impacts. Nothing other than its size and shape is important at this moment – it is considered as a screen.

Then an ecologist shows up and says that he is strongly opposed to cutting down the tree, because it is a very important part of the local ecosystem. It keeps water by its roots and makes the ground firmer. He presents another study modelling the present situation, when the tree is there, and then when the tree is removed. The tree is considered as an inherent part of a bigger complex system.

Thirdly a biologist comes to support the ecologist’s opinion. He presents additional arguments supporting his attitude. He states that moreover this tree serves as an important nesting-place for many endangered birds’ species. Removing this tree can then cause the disappearance of birds from this locality and what is worse, even a significant reduction of their numbers on a global scale. Besides birds there are also many insect species that live in this tree and they are so many that it makes no sense to speak about it any longer and the tree simply must stay in its place. The tree is considered as housing of a whole society of animals.

At this moment the situation looks optimistic for the tree, but suddenly the course of events is reversed. A rude botanist claims that the tree must be cut down as soon as possible, because it is starving from some dangerous tree illness and presents a threat for the whole neighbourhood. The tree is considered as a source of disease.

The auditorium seems to be persuaded by his argument; but not every one is convinced. An old woman stands up and with emotion in her voice starts telling a story of how important a role the tree plays in her life and also in the lives of other people living in the street. All of her earliest memories are somehow connected with it; she remembers herself playing round it as a little child. The tree was a witness of her first rendezvous, both her children slept in their carriages in its shadow, and now it is the destination of her daily walks. The tree is considered as a part of the social and emotional relations in people’s lives.

Now the auditorium is visibly confused. But it is not over yet. In the last row a philosopher takes over and starts to talk about the tree’s “personality”. He presents it as a living being with its own long history and own right to live. According to him no-one is justified in killing it; it would be an ethical violation. The tree considered as a living being with its own individuality.

Regardless of how this meeting ends, it is clear that the discussion was hard. Mainly because every person involved to some extent talked about something different even though they all talked about the same tree casting a shadow at their windows. In Mikulecky’s words each of them interacted with the tree in a completely different way, hence their different statements. Each of them presented the tree as something else and none of these representations were derivable from, or transferable to, any others.

To fully understand the meaning of this scenario is not trivial at all. On the one hand it legitimises the heterogeneity of complexity definitions; on the other hand it shows as an a priori fact that when we succeed to grasp one of the system’s aspects it does not help us to find the others. What is more, we cannot use it for further study because a new aspect acquires a new point of view. All approaches to the system, i.e. all formalisms developed to describe one of its aspects are mutually exclusive and distinct.

Is it so that it is not possible to generate any general model of a particular complex system from a principle? It would seem that the answer to this question is positive. Indeed, it may upset some readers, but if we succeed at looking beyond the false certitude of the Newtonian Paradigm – with us for more than 300 years – that everything is knowable by man because it is simple at its core, we might find it quite natural. The first evidence supporting the fact that reality must be approached form different angles is the plurality of sciences practiced by people nowadays. Their number is already so vast that it would be nearly impossible to mention all of them.

The fundamental natural sciences, as well as all of the applied sciences based on the former, try to find answers to the basic questions about the world we live in, including mankind itself. Mathematics deals with formal representations, and its youngest offspring – the computer sciences – provide not only the essential tool supporting the research, but go in their own direction towards simulating and even creating complexity.[5] Social sciences focus on society and its interconnections. They are interested in man in relation to his environment, and to other people. The abstract sciences - philosophy, theology or history for example – try to find the truth about the world through thinking, arguing, evaluating the past, etc. Literary or art theory deals with the intellectual possessions of man. And there are many more examples of people's activities in searching for knowledge of the world and man, who is, of course at the centre of their interest, as the most sophisticated realization of complexity.

Would anybody suppose that it is possible to derive some political theory from biology? Or use language theory to recognize an illness? I do not think so. Politics, the functioning of organs, using language and changing conditions of health are all aspects of human existence (a few of many). Each of them requires a specific approach, a specific theory and a specific formal system, which, unfortunately, is non-transferable. A general theory or a model involving ALL properties of complexity seems to be beyond our reach. The only thing we can hope to do is to achieve a reduction in these gaps through hard, cross-disciplinary work.

The first step on this difficult road must be made toward the better understanding of complexity itself. We mean complexity as a phenomenon representing the termination of all of the particular paths mentioned above; or, from another point of view, the core, the substrate of all un-reduced sciences.

1. Complexity "per se"

Complexity as an object of study is a fairly recent phenomenon. Approximately up until the middle of the 20th century, complexity was treated as an antonym for 'simplicity'. However, since then, this new discipline has

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[5] Cf. Artificial Intelligence.

experienced huge growth and has divided into many sub-disciplines. There are many institutes and laboratories over the whole world that busy themselves with the problems of complexity theory. Probably the most famous of these is the Santa Fe Institute in New Mexico.

But, it is not our intention to give an overview of this scientific field – it is not even possible to do so in one article.[6] Nowadays complexity studies constitute a huge scientific branch, touching on many research domains. Besides physicists and mathematicians there are biologists, physicians, computer scientists, specialists on artificial intelligence, economists, psychologists and many others involved in complexity research. For our part, we want to focus on the phenomenon of complexity itself and its general description.

The first question we must ask is, if complexity does exist by itself, whether we can consider it as an isolated thing, disregarding everything else. If we find that the answer is negative, there is still the chance that although it does not exist independently from other substances, it keeps its own identity. If this is the case, it makes good sense, from an ontological point of view, to continue to examine this phenomenon. However, if it is true that it is just a synonym for complicated or difficulty – as P. Grassberger proposed (Grassberger 1989) – then the whole topic is nothing more than an empty bubble and a playing with words. To sum up, we are searching for the essence of what we call ‘complexity’.

Complexity is a magic word, such as the word energy for instance. It sounds scientific enough and it can mean almost anything. When we say: “This problem is complex” it creates the impression that we are well informed about the issue, that we are scientifically well educated, and that we know what we are talking about. Unfortunately, the opposite is true. This expression rather serves to expose that we know almost nothing about the problem except that it is very complicated for us. We do not even know what we are saying because we do not know what ‘complex’ actually means.

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[6] To get insight into the issue in an accessible form without too much mathematics we recommend the book by Coveney, P. and Highfield, R. (1995) *Frontiers of Complexity*. Fawcett Columbine, New York (Coveney, 1995).

To some extent it is possible to pass over this uncertainty of meaning by stressing the complexity of the object. That is why it is much more common (and easier) to speak about the complexity of something, rather than about complexity itself. Actually, there are very few authors who have found the courage to write about complexity itself as a subject of study. In most cases we see headings connecting complexity with language, economics, the brain, etc. By adding an attribute to the object we restrict ourselves to one particular issue, no doubt, a clever and far-seeing act. It enables us to speak about things in the concrete, and avoids the danger of losing ourselves in a pool of too general statements and truisms that do not offer the prospect of further exploration. Among others we can mention sayings such as: “Everything is complex and everything depends on everything”; or “Complexity is complex”. Nevertheless, if complexity really does exist it must be possible to deal with it as a phenomenon and as a concept.

Furthermore, when we look into the literature or start to listen to how people use the term ‘complexity’ we find that they more often express it in comparison than in evaluation. We would rather come across the expression “a car is more complex than a bike”, than “complexity of a car is X and complexity of a bike is Y”. This is even more evident in the common language of biology and in artificial intelligence literature. It is absolutely natural to compare complexity of individual neural systems within different living beings or their computer simulations. Nevertheless, one never gets its information on how “big” (or “strong”?) this complexity really is!

Of course, this comparison works better when one compares things within the same system or things of the similar nature: e.g. cell & organism, calculator & computer, sentence & poem etc. In fact one gets into serious trouble when wanting to compare completely different things: e.g. computer & poem (Edmonds 1999: 1). (This kind of attempt could be easily be seen as absurd). Nevertheless, in this case the ability to determine a particular value for complexity would be very useful. Unfortunately, this is something that we have not been able to do till today. We have no frame of reference, no standards by which to measure complexity. Complexity is for us a quantity without any absolute value. Now the question is, if the reason for this lies in our limited abilities, and would the brother of the famous LaPlacean Daemon[7] – let us call him the Complexity daemon – grasp complexity, or is its "ungraspability" a latent attribute of complexity, arising from its nature? For now we must confess that we do not know.

In a great number of works complexity is attributed to descriptions of models and not to any real systems. Some people– for example B. Edmonds (Edmonds 1999: 6) – are convinced that there is actually no way other than to estimate the complexity of the model of a given system and then to apply it to the system ex-post. Furthermore, they believe that it is not useful to speak about the complexity of a natural system because this "quantity" is very vague and strongly depends on the distance from which one observes the given system, the number of aspects involved, the variations of the chosen framework, etc.[8] Edmonds gives the following definition of complexity:

> *Complexity is that property of a model which makes it difficult to formulate its overall behaviour in a given language, even when given reasonably complete information about its atomic components and their inter-relations.*

As one of the most important aspects of this approach (meant to be beneficial) the author inserts the fact that complexity is no longer applied to natural systems, but rather to models. From now complexity is understood as global characteristics of a model. It follows that "complexity is the difficulty of finding a description of the overall behaviour of a model". But, since this description is also a model description, we are actually looking for "an overall model description of the object model". So, what we are really exposed to is a "model^2".

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[7] Let us remind ourselves that the LaPlacean omniscient daemon is an idea representing the classical deterministic belief that if someone (a daemon) knows all the initial conditions of a system, and in addition, all the agents acting on the system at every moment, hence he would be able to predict the future of the system in any following moment, exactly.

[8] Let's remember the story from the beginning of this chapter about the meeting that was called decide whether or not to cut down a tree casting a shadow at some houses in the centre of a city. Each of the specialists involved in this process had made a model of a situation according to his own specialization. The tree was represented by a model too; it was a "model inside a model". Actually, none of the people spoke about the tree on its own, other than the philosopher. The philosopher's approach was, however, also different in another fundamental aspect – it had no intention to address the 'quantity' of the issue, but rather the 'quality'.

Now, one can raise the question as to how these people understand the natural system standing at the beginning of this exercise if at all. B. Edmonds gives a following answer:

> Identifying *whole* systems is problematic in general. Many natural systems are causally interconnected, making any division seem somewhat arbitrary from anything approaching a general viewpoint. This problem is not solved by the seeming ease with which we actually *do* assign useful identities to systems as this seems to result at least partially from blend of psychological, pragmatic and accidental features. There may well be true philosophical aspects of this distinction, but since we are restricting ourselves to particular representations of any system in a language this is not a problem for us; we *decide* the level of interaction of the system with the rest of the representation when we specify our representation and *assign* an identity to some portion thus making it our focus. This does not eliminate the problem, of course, as it then becomes critical *how* we model any real system if we want to discuss the complexity of an aspect of it, but such concerns are common to many aspects of using representations of real systems.
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> So for us a *system* may just be a collection of statements intended to describe it sufficiently. We necessarily decide questions of system identity as a by-product of representing the system to start with.

The natural consequence of such an approach is the ultimate shift from reality to representations. No doubt, this way is much more easy and useful if the goal is an exact formal description of a given system and mathematisation of the nature. However, one should be aware also of the hidden danger in such an approach. When the distinction between reality and its model is wiped out then both can easily be interchanged. As a consequence statements about models are interpreted as true facts about the nature; and the reverse effect is such that nature is “forced” to behave according to model predictions.[9]

There are two ways one can explain this inclination to modelling rather than dealing with reality itself, when it comes to connection with complexity: 1) because it is too difficult to deal with complexity per se or, 2) complexity by itself does not exist; complexity is just a matter of relation between two things (two natural systems or system & its model). In other words, complexity

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[9] As we will see, it happened to some extent in quantum mechanics.

without a proper object does not make any sense. Nevertheless, even if this is the case it does not mean that complexity has no essence!

In Edmonds's definition, as quoted above, complexity is related in a sense to difficulty. It is not his intention to identify both, but it is true that this identification (at least implicitly) often occurs. It is obvious that both these terms, i.e. 'complexity' and 'difficulty', are very close to each other. However, as we understand them and use them in this text, the content of the word "difficulty" is wider.

There are many things that can be "difficult" for us: math exercises, situations in our life, politics, washing machines, the human brain. From the first glance it is clear that all these examples differ considerably in their nature. A math exercise can be objectively difficult to solve, because of its many parameters for instance, but in most cases this statement is purely subjective. It is difficult for *me* because *I* do not have enough knowledge to solve it. The second example is similar, although it is not only about knowledge but also about personal involvement, emotions, feelings etc. But, one friend who is not involved in this situation can give us a disinterested advice and the whole problem might be solved. Politics, on the other hand, is really serious for most people, and, in a global sense, it is objectively unknowable. A washing machine is also considered by most people to be a "complex thing" but actually it is not. On the other hand, a human brain is, without a doubt, complex.

What we try to demonstrate using these examples is that when trying to be correct, one should distinguish between difficulty due to complexity and difficulty due to ignorance (Edmonds 1999). So, the range of the possible meanings of the term 'difficulty' is actually wider than we first thought. The difficulty in describing a system can be caused by our insufficient knowledge, but the system itself can be entirely simple; ruled by simple but unknown mechanisms. That is why someone can only speak of complexity if he or she knows enough about the system to prevent this kind of confusion.[10]

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[10] By "enough" we mean "knowing a reasonable amount about its components" without any further specification, depending on the particular situation.

What is clear from what we have said up to know is that complexity is something that can only be attributed to an object. Like colour, for instance, which can be well defined in terms of the wavelength of light; but without specifying what possesses this particular colour what meaning will be left? Surely something like whiteness exists, but it is another kind of existence, so to say, than the existence of a substance (this statement needs further explanation, which will be given shortly). However, we are still convinced that there is an ontology connected to complexity, simply because, so to say, until now, we have not found any strong evidence that it is not so.

According to Mikulecky (Mikulecky 2001: 341), if there really is an ontology associated with the term 'complexity', complex systems must posses something that complicated and simple machines do not. About this something one can only say that it must be lost when the system is reduced to its parts. The essence of the ontology of complexity lies in the existence of this something. A machine-like system is nothing more than a complicated arrangement of its parts. It is possible to decompose it and to compose it again without the loss of any of its properties. But, this is by no means possible in the case of complex systems!

In the course of our discussion we have come to another important question: how does complexity originate? Where does it actually come from? Before we try to find an answer we must pay attention to one more aspect of complexity, i.e. its temporary character. Not only does complexity not have any exactly determinable value, only a comparative one, but it is not constant at all! Complexity changes in time according to the evolution of its carrier. Strictly speaking, it results from the interaction between the components of a given system.

This finding represents more support for our previous assumption that complexity is naturally tied to a given system; it is a predicate attributable to the subject (system). So, it turns out that the right answer to the question raised before is that complexity does not exist by itself but belongs to a substance. To clarify this statement philosophically we will address ourselves to St. Thomas Aquinas[11] who is the author of the theory of substance, which has its origin in the thoughts of Aristotle already[12].

According to this great thinker the world we live in is composed of material things – substances – that have their own identity; they are unique and unalterable. Substances are beings that are sharply bounded and they differ from one another.

The proper determination that constitutes a being as *this* being is expressed (in contrast to 'existence') by the term 'essence'. So, in the content of the term 'being' we may distinguish an essential aspect, i.e. what the being is, and an existential aspect, i.e. that it is. Essence is a determination of being, hence if there is an essence then there must be a being as well.

Aquinas adds that some things share their being with other things but they are not always enclosed in each other (in *II Phys*., lesson 3, n. 161). L. Elders (Elders 1997: 67) explains it as follows: "in a 'white musician' 'white' is not contained in 'musician'. For this reason the one can be thought without the other. In natural things there is always something which is prior to and more fundamental than other predicates." So, predicates differ in their magnitudes, in a manner of speaking. In our sayings we most often connect a predicate with a substance by using the copula "is". But, in different sentences this copula can possess different meanings. Cf. "Socrates is a man" and "Socrates is bald". This fact was already observed by Aristotle who declared such predicates "fundamentally different". These thoughts were more elaborated by Aquinas who gave them their final form.

Aquinas distinguishes the following modes or categories of being (Elders 1997):

> To make this clear one should know that being is divided into ten modes of predication and that this is not a univocal division, as a genus is divided into its species, but a division according to different modes of being. These modes of being correspond to the way in which a predicate can be attributed to a subject. If we predicate something of a second being we say that this being is this predicate. For this reason the ten modes of being are called the ten ways of predicating (predicates). However, every statement in which something is stated of something else, is made in one of the following three ways: [a] A first way is when what belongs to the essence

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[11] St. T. Aquinas (1225-1274)
[12] Aristotle (384-322 B.C.)

of the subject (of a sentence) is said of it, as is the case when I say “Socrates is a human being” or “man is an animal”. In this way we speak of the predicate of a substance. [b] A second way is when something which is predicated of a subject does not belong to its essence but nevertheless is within it. This can be with regard to the matter of the subject and so we obtain the predicate of quantity (for properly speaking quantity is consequent on matter; for this reason Plato connected “the Great” with matter); or it is with regard to form and so we obtain the predicate of quality (for this reason qualities are consequent on quantity, as a colour is on a surface and a figure on lines and planes); or it can be with regard to a second being. In this way we acquire the predicate of relation (when I say: this person is a father”, I do not ascribe anything absolute to him but a relation which is in him to something outside). [c] A third way to state something about a subject is to predicate something of it on the basis of what is outside, by way of denomination. In this way we state extrinsic accidental determinations of substances…

Denominating a thing from what lies outside it can be done in a way which, in a sense, is common to all things, and in a way which is peculiar to the things which belong to man. Something can be predicated of something from what lies outside it – and that in a way common to all things – either according to what is characteristic of a cause or according to determinations of measure. The reason is that that which is caused or measured, is denominated from what lies outside it. There are, however, four genera of causes, two of which are part of the essence, sc. Matter and form and therefore predication according to these two belongs to the predicate of substance, as is the case we say that man is a rational or a corporeal being. The final cause does not produce anything in isolation from the efficient cause. Therefore, we are left with the efficient cause as that from which something can be denominated as from the outside. If something is denominated from the efficient cause, the predicate of undergoing (passio) results, for undergoing is nothing else but receiving from the agent. Inversely, in as far as an efficient cause is denominated from the effect, the predicate of action results, for to act or to do is to realize something in that which undergoes the causal influence of the agent…

With regard to measure, one type of measure is intrinsic, a second extrinsic. An intrinsic measure is, for instance, the length, width and depth proper to each thing; something is denominated from them as from that which is intrinsic to it; for this reason “to be measured intrinsically” belongs to the predicate of quantity. The extrinsic measures are time and place. In so far as something is determined under the aspect of time the predicate “when?” results, and in so far as it is determined under the aspect of place, the predicates “where?” and “in what position?” result. The latter adds to the “where?” the order of parts in a place. It was not necessary to add such a further determination to time, because the order of parts in time is enclosed in the concept of time, for time is the number of a movement according to before and

> after. In this way “when?” and “where?” are predicated on the basis of their denomination from time and from place.[13]

Let us take as an example the following statement “A human being is a complex system” and let us try to decide what kind of predicate it represents according to Aquinas’ division. (We find this categorization as useful for further study of this topic because when we know what we are dealing with, we automatically know better how to deal with it.)

First, we shall look at how the predicate ‘complex’ is attributed to a subject. In our example we have as a subject ‘a human being’. ‘Human being’ is a substance with its own characteristic essence. The essence is something makes a human being *the* human being; In other words, what distinguishes this particular substance from other substances and creates its identity. Can we say that being complex has such ability? Can we think about a human being without seeing his or her complex aspect? It seems that we cannot. But is ‘being complex’ an attribute proper only to man? Unfortunately, the answer to this last question is also negative; and it signifies a problem. ‘Being complex’ appears to be too general to allow us to consider it as belonging to the essence of human beings.

So, let us move to the second way of stating something about something else as Aquinas proposes. In this regard he distinguishes among different predicates which do not belong to the essence of a subject, but which are nevertheless within it; predicates of quantity, quality and relation, among others. From what we already know about complexity we can immediately conclude that ‘being complex’ is described neither by quantity nor relation; to be more correct, it is much more than these two. It is true that complexity appears when some criterion of size is fulfilled and that the value of complexity is rather comparative, but at the same time complexity is more about the nature of a system than about its outer attributes.

Thus, what remains is the predicate of quality. According to Aquinas, quantity is consequent on the instant, on matter while quality is with regard to

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[13] Aquinas, *In II Phys*., lesson 3, n. 161.

form – as follows from the Aquinas-Aristotelian doctrine of matter and form.[14] So the question now is if it is possible to connect 'complex' with the substantial form. To get the answer we must examine the theoretical situation of 'the loss of complexity'.

An old pullover can lose its colour but it still will be a pullover. A wax candle can be melted but it still will be a 'wax thing'. However, when the complexity of a brain is lost then its parts do not cooperate any more and the whole brain ceases to function. It is dead and the whole organism with it; it is only a mixture of chemical compounds remaining from the living being. Nothing of its essence is left. As R. Rosen puts it: "Complexity is almost another way of saying these systems are alive" (Rosen 1997: http.). Disregarding the extent to which this statement can be regarded as equivalent for the moment, we can re-formulate our initial sentence as follows: "A human being is alive". And this is a proposition we understand much better because the word 'alive' is familiar to us although there is no final definition of 'being alive' either.[15]

When speaking of 'being alive' no one would hesitate to connect it directly with the essence of the particular substance. But what is in some respect special about this predicate is a fact that it is rather general. Of course, the content of the term 'alive' or 'complex' has a slightly different meaning from system to system, but it is not possible to say that a dog is alive "differently" than a man, or that a language is complex in a manner different from a brain. 'Being alive' or 'being complex' is not a predicate proper to the particular substance, but to a great number of substances; although its realization in individual substances is not identical. So, from what has been said up to now, we can conclude that complexity – as we understand the term – stays on the edge of Aquinas' first mode of predicating, i.e. a predicate of substance, but it surely belongs to this category.

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[14] Each thing, which is a subject of change is composed of matter and form. In the process of substantial change a thing loses this form and receives a new one. As when wood burns to ash. In this process the matter substrate does not case to exist but it adopts a new substantial form and a new substance is formed. The matter substrate that is common to all things is called primary matter, *materia prima*.

[15] Obviously there are many definitions of live it is possible to find within the different literature but no one can be considered as a final one, describing this phenomenon in all its aspects and richness.

To define complexity as a predicate of substance is vital, with far-reaching consequences. If we treat a given system as not being complex, but it is complex, we actually change its very nature. In other words, we deal with a substance different from what we suppose! Fortunately our experience shows that this mystification is not so crucial for scientific applications and technologies, but it is very important for philosophical evaluations, which need to be ontologically correct.

After attributing a making some philosophical categorization to the term “complexity” we can move on to another question: Can we know complexity? For the present we will confine ourselves to the general question as to whether or not it is possible to know complexity at all; and if the answer is positive we will leave aside the “how” question for the moment.

Complexity is not only a quantity without any absolute value as we stated above, but it has another feature that complicates the problem. Complexity manifests itself differently according to the distance from which one observes the system, and according to the task one follows; in other words, according to what one “wants to see”. For example if we observe an anthill[16] from a great distance we do not see more than a hill of something. If we come closer we can see some movement on its surface. Another step brings us closer and we know that there are thousands of small animals living in this hill. After some study we are even able to recognize schemas of their behaviour, the hierarchy ruling their society, and much more. Moreover, there is the completely different view one gets when one comes even closer, with a proper viewing device and focuses one’s attention on one ant. The observer does not see the whole hill any more, but only a single animal that behaves “strangely”. Strangely that is, for the observer that he knows nothing about the society that this particular ant is part of.

The reason why the unknowing observer would probably regard the behaviour of an individual ant as strange lies in his or her personal experience that every living being lives to some extent, “for itself”. It acts in its own benefit

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[16] A society of ants living in one anthill can be regarded as a complex system, for the number of its members is large enough and they create non-trivial relationships that evolve in time. But, a single ant itself is a complex system of its own just like a single cell, for example. At the other side of the scale, the whole anthill is the part of a complex eco-system of the forest and so on.

as an individual: to nourish itself and its family, to breed its own offspring, to assure its own safety or the safety of its family, etc. The global aspect of such natural behaviour is usually not considered spontaneously, but demands a little of further knowledge. From this point of view and without more information a single ant that fills its own life with repetitive work – and moreover with the same kind of work – is totally incomprehensible.

Let us imagine that our observer wants to know more about this single ant and for this purpose will use some optical tool. Now he is able to observe different parts of the ant in detail, he can see its individual cells; and if he is really well equipped, he can even carry on to the domain of atoms and nuclear particles. However, will this effort really help him to reach his goal? What can the individual cell or even deeper lying chaotic movement of electrons round the carbon nucleus tell us about this ant in particular and about the anthill as a whole? Almost nothing.

It is a matter of a fact that observing one single ant does not help us if we want to understand the ant society. On the other hand, staring at the anthill for hours from a distance cannot assure that we will see all its inhabitants. Some of them will definitely stay hidden from us. This confirms our proposition that in the case of complex systems everything depends on the distance between the observer and the observed system, and on what the observer wants to find out.[17]

Does it mean that all knowledge concerning complexity is only relative? Can it even be true that we cannot reach any knowledge about complexity at all? Realistically the answer is “no”. If we accept that something like complexity does exist (even if only within some or other substance) it must somehow influence the knowing subject, i.e. the knower, even if it stays outside the knower.[18]

How to explain the process of cognition is a matter of everlasting philosophical dispute. It is not our ambition to try to “solve” this problem. To sketch it we mention only four main streams of thinking relevant to our work, given by (Elders 1997: 173):

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[17] Cf. Hofstadter, D. R. (1979) *Gödel, Escher, Bach: an Eternal Golden Braid*, Basic Books.

[18] In this section we restrict ourselves to understanding the philosophical problem of knowing complexity.

Plato proposes the following theory of identity of the knower and the known: things exist (according to their essence) as pure forms (in the world of Ideas); and the intellect thinks by participating in these forms. In his view the body does not really contribute to intellectual knowledge and is superfluous. If we allow ourselves to simplify and paraphrase Plato we would dare to presume that somewhere in the world of Ideas the pure form of complexity exists.

To "apply" Plato in such a way to complexity is, however, ridiculous. Partly because it is a subject very different from what was envisioned by Plato, partly because complexity probably cannot be understood as a steady bearer of the essence (i.e. substance). Its character is rather accidental.[19] Thus, one cannot attribute any unique essence to 'being complex'. So, to imagine a 'pure form' of complexity in Platonic sense is rather difficult. Thus, Plato probably does not much help us to solve the problem of knowing complexity.

Aristotle on his part – and followed by Thomas Aquinas – asserts that reality communicates itself to beings endowed with cognitive faculties; the latter receive the knowable contents which things pass on to them. This is the position of classical realism, which works quite well in the case of 'ordinary things'. Let us illustrate this using the following example: If I look through the window the first thing I see is the huge building of the Institute of Mathematics. As a human being I am endowed with eyes and memory so I can immediately decode the information that this particular building passes on me. If it were another person instead of me, who did not have the same knowledge I have, he or she would still be able to recognize the thing we are looking at. He or she would probably not know that it is the Institute of Mathematics, but would nevertheless be sure that it is a building. And from the substance point of view, this is satisfactory. It is completely the right answer. Likewise thanks to my cognitive faculties I am able to identify this particular animal running around as a dog. I do not know what kind of dog it is, nor anything about him

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[19] Accidents are consequent upon substances and the first of them is accident quantity. It means that quantity is the first determination of the thing and at once the main subject of natural sciences. Accidents are predicates of the substance. Accidents, for their part, have essence only "to some extent" as Aquinas said. By "to some extent" is meant that their definition is never complete, for the definition is always also entered by the bearer of the accidents.

as an individual, nevertheless I have satisfactory knowledge of him coming to me from him through my eyes and my brain.

The first condition to obtaining objective knowledge about an object, however, is that it must be unchangeable. By 'objective', when speaking about knowledge, we mean “that which expresses something existing, not constructed by our knowledge”. The objective knowledge defined here implies a true statement about objects that states their fundamental determination, i.e. that they are (Fuchs 1996).

Unfortunately, this nice and simple theory is not suitable when one starts to deal with intricate pieces of reality that are not simple but complex. In this case the content a complex thing passes on to its observer is far from being unambiguous and apposite. Sometimes it is even so vague that it evokes no particularity in us. Or it is so unstable that it changes quickly according to different angles. So, the Aristotelian-Thomistic doctrine does not satisfy us either. We do not want to say that it is wrong, but rather that it does not take these kinds of objects, i.e. complex objects, into account. Things that are absolutely natural for the complexity problem is fairly new.

As we pass on to modern philosophy, we should first mention Immanuel Kant[20], and then Jean-Paul Sartre[21], who is a representative of existentialism. Kant for his part was convinced that the form, which the known object acquires in the knower, comes from the knower himself.[22] According to Kant, the senses and the intellect add these forms to, and impose them on, the brute material coming to us from the outside world. An even more extreme point of view is that of Jean-Paul Sartre. He argues that to a great extent man himself determines the properties of things and their meaning (essence). Although these two positions differ significantly, they have something in common. They do not believe in the existence of an objective reality independent of man, with its own sharp strokes that man could observe and know. In other words, they make the term 'objective' subjective.

If the content of the term ‘objective’ (i.e. a cognitive act expressing something not constructed by people’s knowledge) were itself subjective, then

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[20] I. Kant (1724-1804)

[21] J.-P. Sartre (1905-1980)

[22] By ‘form’ is meant properties that generally determine things.

things constructed by a cognitive act would have a purely subjective origin and it could not express something not constructed by the knowledge. A reflection stating this subjective position uses the term 'subjective act', which is, however, stated as objective, i.e. as an act expressing something not constructed by knowledge itself. But, according to this subjective thesis this act must be considered as subjective as well. Thus, the subjective position is, according to its proper meaning, unknowable. Although it presents itself as knowable – it cannot act in another way – it contradicts itself. Thus, we can consider the objectivity of the term 'objective' as almost verified. The negation of objectivity leads to the cognitive nihilism (Fuchs 1996); and this is not the path we want to follow.

After all that has thus far been said, we can ask ourselves if the question *“What is complexity?”* has any sense at all. We propose that the answer is “yes”. However, we can probably not understand this question as a question about the essence of complexity, for this kind of question can only be put in the case of a substantial being, where its existence is objective and evident. Even though this conclusion is vital for philosophically dealing with the problem of complexity, it does not have any significant value for the scientific treatment of complexity. After all, looking for essences of things is not a subject of (natural) sciences.[23]

What should be also stressed is the fact that complexity itself is a complex notion that combines compositional, structural, and functional elements. It causes the effect that things can be complex in fundamentally “different ways”. This is a topic we are going to discuss in more detail in the final section of this chapter.

2. A complex system is an open, natural system

Systems that the world is composed of are traditionally divided into three categories: simple, complicated and complex; however, this division is

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[23] This is absolutely true but the question is if it is also right. The total ignorance of the essence of things and focusing only on the quantitative aspects of things by natural sciences can be misleading when dealing with reality in a broader context, particularly in the case of complexity.

far from being unambiguous. Strictly speaking and following our conviction as stated at the beginning of our treatise that "The entire world is complex" we should rather say that the things that the world is composed of, are divided into these categories according to how they are *cut out* from the complex world system.

The earth, the moon and the sun compose a simple three objects system. This is true only when we ignore the influence of the rest of the universe and consider only these three bodies as simplified physical objects. For the moment we will forget about the changing seasons on the earth, about the tides, and the whole complex of life. To determine the mutual movements of these three objects is a simple exercise from basic physics since the time of Newton, who, on April 28 1688, presented his *Principia*, where he formulated his basic laws of motion, to the *Royal Society* in London[24] in so doing providing the foundation for the whole of classical mechanics. It is even possible to say that classical mechanics is, generally speaking, a science of simple physical systems.[25]

A task that is a bit more difficult is to explain to the reader what we have in mind when we speak of "complicated" systems. Of course, there are many traditional examples, e.g. a Boeing aircraft or a computer that are both examples of by manmade objects. For our purposes, however, it will be more useful to keep to natural things. A good source of examples of complicated systems is chemistry. Individual molecules and their mutual reactions are systems that behave quite deterministically. To describe them fully is, however, a rather sophisticated task requiring knowledge of a great number of parameters and a deep insight into the reaction mechanisms. Existing computer software for modelling in chemistry works well, but it is far from being simple. All this is pretty complicated even though it only deals with simplified, "cut out" pieces of reality.

The last item on our list of categories of world systems is 'complex systems', which is, contradictorily on contrary the easiest to exemplify. For,

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[24] In all of this work, no doubt the highest importance was ascribed to the Third Book called *"The System of the World"* describing the general law of gravity.

[25] One of the fundamental notions of classical physics is a mass point, which is nothing more than a general term standing for any simple physical object and present in most classical mechanical definitions and equations.

almost everything in nature can be considered as complex. One cannot make a mistake when set a half mesh between a life and complexity; all systems that are alive are certainly complex.[26]

Nevertheless, to give some systems the "privilege" to keep their complexity does not mean that these are left aside in the process of simplifying and cutting out from the wholeness of reality. To do so is actually the basic condition for man to be able to grasp each system somehow. Moreover, to "cut out" things in order to see them, understand them, and to be able to communicate with them is one of the basic natural faculties of human beings. Why it is so, we do not know. When we look at the manners in which people "see" the world surrounding them, we find that man naturally experiences the world as a plurality of different substances (Elders 1997). Each man watches himself as a being clearly distinct from his environment, since we can see and touch other things. On the other hand we count ourselves as part of the whole world. However, the testimony of our senses is so strong that the ideal of distinct substances making up the world is very natural to us.[27] So, when we speak of simple, complicated, and complex things we actually express how we categorize substances.

To determine which things are distinct substances is a very difficult task. The classical definition says that a substance must *act as a whole*; it is an autonomous being and a centre of reality. The first criterion to call a single thing a substance is that it must be surrounded by bodies with different properties, and have a typical an distinctive way of operating. The second criterion has to do with the activity of a thing. A substance must have one way of operating that arise from it, because this way of operating is an expression of its being.[28]

At this point we venture to make a statement, which we shall try to defend later on. This statement is as follows: *So far, all known examples of*

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[26] This conclusion was already mentioned earlier in connection with Robert Rosen.

[27] It is our conviction that such a view, asserting that seemingly different things are really one being (as in Brahmanism) must be learnt, it does not come spontaneously.

[28] With regard to artefacts, a machine composed of several parts does not form one substance whereas a cast iron table, in one piece, appears to be one substance. Recently disputes arose concerning colonies of single celled organisms that, under the specific conditions, behave either as a collection of single organisms or as a coherent whole, i.e. one big organism (Coveney 1995).

complex systems are natural systems[29] Thus, in the next step we shall try to define natural things. According to the Aristotelian–Thomistic definition natural things have the principle of some form of movement and rest in themselves (sc. local movement, alteration and growth). Things that are not produced by nature, but fabricated by man, do not have any principle of movement within themselves, except per accidents, i.e. in so far as they consist of some natural material, which can undergo changes (Elders 1997: 56). The intrinsic movement of natural things represents alteration and development.[30] Along with such movement some new qualities can be brought to the object of the change, i.e. something new comes to being.

One of the many realizations of this principle is the growth of plants, particularly of trees – we use their wood for making furniture, for instance. Other examples are moving herds of cattle searching for water; or the aging of cells, which are part of the human body. While growth and local movement are typical and exclusive acts for living beings, the phenomenon of aging and other quantitative changes that are connected with aging are more general. They can also concern manmade things; not directly but by affecting the material that they are made of. A wooden table will change its colour over time, and if not suitably treated it will decompose one a day. A masterpiece of oil on canvas will loose its colours and later fall to pieces when not conserved properly. Even machines made of steel are not eternal. And, all this is absolutely natural.

Thus, when dealing with natural things one should distinguish between either quantitative or qualitative changes that are natural to them, i.e. flowing from their nature, or changes that are imposed on them by man. Metals certainly have the natural inclination to become corrosive, but not to become a screw or a wire. Hence, the forms man gives the natural objects to some extent represent an expression of men's power. We are encountering here a process that brings forth something new.

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[29] This is only a one-way implication for natural systems can be both complex and complicated (and simple). A stone lying on a beach or a snowflake are, respectively, examples of simple, and complicated natural systems, while a living cell is seen as a complex natural system.

[30] When we speak about "development", "evolution" etc. we do not have in mind any periodic movement but rather a continuous progression in a direction to some Goal, which at the same time, represents external or internal measure of this progression.

This last statement is brings us to another important issue closely connected with emerging novelties: the *principle of causality*. According to the principle of causality, every new thing that originates has a cause. It means that, at least theoretically, it should be possible to decode one step backward on the scale measuring time and being led to the origin of the thing under study. This “thing” can be a new being or an attribute or an act, etc. Moreover, nothing can originate from “nothing-ness”. Thus, there must always be “something” particular in each of these steps continuing backward till the very beginning, the sc. *First Cause*.

An important implication of the principle of causality is that this cause itself must possess a perfection that is passed on the changing subject. Another important implication is the existence of the arrow of time. On the other hand, experience shows that the imperfect, i.e. less equipped, seemingly always precedes the perfect; more complex systems always develop from less complex ones. It follows that there must be some cause which encompasses the entire process of evolution and direct it by perfecting the natural capacities of things.

The question we must put now is “What is this cause?” First, we must distinguish if it is an outside cause or an inside cause, residing within the given system. If we choose the presupposition that it is an outside cause then one can start to wonder what is actually outside the general complex system? If we accept that each system represents a component of a bigger system, which is a component of some meta-system then there can be only one Cause which, is outside everything, i.e. God. If we limit ourselves only to one particular system we can admit influence of another, more advanced system or the environment, too.

If we concede that this cause can also be inherent to the resulting system we must, however, ensure that it would not be a part of its essence. In this case it is inside the system but at the same time still outside the resulting thing. Thus, although we initially distinguished between outside and inside causes we are actually still keeping with a kind of outside cause. And this allows us to make the general conclusion that *each process of forward evolution is encompassed by an outside cause*.

Moreover, if we accept that this cause does not have to be literally outside the system, but the later eventuality very well can be true, we can avoid many difficulties resulting from the possibility that the problem is now shifted to the purely metaphysical level, without any possibility of using a scientific approach. In fact, setting this cause inside the system, but outside its essence, allows us to represent this cause in scientific, particularly physical terms. Without any ambition to resolve what this cause actually is we can guess, for example, that it can be a structural development or self-organisation and the like.[31]

From what we have argued in the preceding paragraphs we, can conclude that *complex systems must be open systems,* connected to an outside cause, as was specified. Moreover, no evolving system can be produced just by one initial pulse without any continuous intervention of its environment, a second system, or some other cause. The reason is that no development and no evolution is in fact a single act but is rather an everlasting process continuing as long as the system itself exists. In this process one change follows the other; they mutually complement each other. Natural evolution on all levels seems to progress smoothly, without any jumps[32] (even though progress is often not a straight line, but follows many curves and blind ways).

What has been argued in this section has far reaching consequences for man and his creative activities. It seems evident that man (if not God) cannot create a system that could further evolve itself in any single act. The only possibility seems to be that man – creator – will stay connected with it supplying it continuously with new information. But this is not the only restriction that follows from the forgoing results. No man can supply the system with a complete cause; this would be beyond him. He can only initiate it. This cause cannot be the same as the man himself because every man is limited by knowledge of himself, and he is an open and changing, i.e. an evolving system as well. In other words he cannot know himself completely

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[31] In the course of the following chapters we will deal with these terms in detail and we will speak, for example, about such phenomena as complexity enhancement in nature, so an inquisitive reader won't be left only with partial information.

[32] This finding even enters theological discussions, adopting the form of questioning if the creation of the world as we know it today is a result of one initial act of God, or if God is still "working" on it.

and thus he cannot copy himself in any way. Therefore, all he can give will always be less perfect then he is himself. And the same is true for the cause he can use to initiate a new complexity.

We have finally come to one of the most fundamental conditions for being complex: the impossibility of any exact description, and non-deterministic behaviour. This is why, in principle, no man can produce any complex system with all its perfections, being beyond his own conscious and known faculties. At most he can start it and leave it to join another encompassing cause, which would bring it to its perfection. However this “other cause” would certainly be based on some natural principle – it would be a *natural cause*. And this is the reason why all known complex systems are natural systems (if we dare to exclude the classical concept of God as Creator and as the Cause of everything, which we do not consider as beneficial for further scientific treatment of the problem of complexity).[33]

3. Natural things consist of parts while composed artefacts are created from pieces

A natural thing represents one substance that is continuous and undividable. By a continuous whole we mean a whole whose parts touch each other in such a way that there is nothing between them and they have limits in common (Elders 1997: 141). So, parts of a natural substance are connected by a common, indivisible boundary. This is easy to demonstrate on such substances as, for example, an iron pole or a wooden clog. For, these are homogenous bodies. Although we are aware of the fact that individual plant cells are composed of individual atomic crystals, we do not perceive them as a collection of “sub-substances”, but as a continuous whole.

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[33] This result has far reaching implications for research concerning artificial intelligence. If we ask if artificial intelligence is in any way possible our answer is that from the point of view of classical philosophy (although a little modernised) “probably not”. We say “probably” because there is still a room left for the possibility of initiating of some “complex jump”, which could bring the system into a state of self-evolution or communication with some as yet unknown meta-system, which posses all the necessary perfections. But, up to know it seems that this possibility is rather unlikely. Even the most sophisticated computers and the most advanced technologies are still very limited in their “own lives” (Conveney 1995).

When we make a step from a wooden clog to the whole living tree, a situation a bit more complicated emerges. Each tree generally consists of roots, trunk, branches and leaves. Each of these parts looks differently and acts differently to some extent.[34] It is possible to cut out one root and to show it to others. Everybody will probably recognize it as a root of a tree. In the same manner we can break off one leaf, which is a bearer of even more information. It will tell us about the kind of the tree it comes from what is not so easy in the case of a root. Moreover, if we do both these things the tree itself won't be hurt. On a small scale such loses of its parts are not deadly.

The difference between the living tree and their cut out parts consists in the fact that the former continues in its existence as a tree, while the later after a time cases to exist at all. Even if it is put into the ground and a new tree starts to grow from it, it ceases to exist as a leaf.[35] The existence of a tree is prior to the existence of its parts. To exaggerate this statement one can say that a leaf without a tree means nothing. However, the opposite is not true.

A completely different situation can be found in man-produced things. A composed artefact is a whole, which is made from pieces that represent things that differ both in their properties and their typical operations. Pieces have boundaries that can be traced. For instance a table consists of a top and four legs. When we remove the legs the table ceases to exist as a table but when we add new legs to the top (even completely different ones) a "new" table is born. Another example is a screw used in a cupboard to put its components together but can well be used for other purposes. Being in a new box for instance, nobody recognizes that this is the screw from the cupboard. Conversely, a butterfly wing is a part of a butterfly but in a different way

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[34] We say to some extent, because as being a part of the living whole in the last approximation every part must be ordered to this whole. Thus, its acts are also performed for the sake of this whole.

[35] The possibility to grow a new plant from a single leaf or a branch somewhat clashes with the theory of vitalism attributing some "vital forces" to living beings, which provide their "biological integration" and seats these forces into the "heart" of living beings. In fact it rather evidently supports the theory of genes, seating all of the information about the organism in every individual DNA molecule. Even stronger evidence for this can be found in recent successfully performed clones of some organisms from just one single cell. Nevertheless, what we can stress here is the fact that, at least from the philosophical point of view, *a leaf is not a tree* (if , then only in potency).

completely from a leg of a table. It cannot exist without the particular butterfly and it cannot be substituted by anything else of a different nature.[36]

Aquinas (according to Elders 1997) gives the following definitions of a part of a natural thing:

- a part conveys no information about the nature of the thing of which it is a part, but expresses only a relationship to the whole of which it is a part;
- a part in itself alone is unfinished;
- a part is a piece only in potency[37]
- parts are connected by continuous limits, their surfaces coincide and together they create a continuous thing.

No natural things – either complicated or complex – are ever composed of pieces but always of parts; for they form a coherent whole, where all its parts act in accordance with its substantial nature. As a result a new quantity emerges, which is in fact, the essence of the substantial whole. Everyday experience provides strong evidence for this conclusion. Hence, *the whole is* always something *more than a sum of its parts*[38] or in another formulation: *more is different*[39]. For instance, a molecule of water is more than just two atoms of hydrogen and one atom of oxygen[40] a man is more than just one head, two arms, two legs etc.

In actual fact, we have come from the other side to the same conclusion we proposed in part 1 of this chapter. If we formulate a thought experiment and decompose an arbitrary complex natural system into its parts, something will invariably be left. And this "something" is to some extent the representation of the complexity proper to this system. However, this is not the case with artefacts. These are easily decomposable, and when finished

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[36] However, it is very well possible in the case of a table where the original wooden legs can be easily substitutes by iron ones, i.e. by parts of completely different nature.

[37] It does not exist independently (except perhaps only shortly or under some special conditions), i.e. its separate existence is unstable.

[38] This is a famous statement of Robert Rosen.

[39] According to P. W. Anderson (Anderson, 1972)

[40] One cannot consider natural forces (physical, chemical etc.) to be substances, only accidents.

nothing besides their parts – pieces – is left. This is an argument strongly directed against reductionism.

We are well aware of the fact that when we align ourselves with the strong antireductionist position we are in a considerable danger to fall into primitive holism stating that everything is entangled with everything and that there is nothing more to say. However, this is not our intention – the opposite is true.

To sum up, if we adopt the thought of Robert Rosen that complexity is another way of expressing the state of being alive,[41] we should think of these systems as composed of parts, that cannot be considered as isolated "pieces of a matter", but only in the whole context. This is something that we shall keep in mind because it will turn up as crucial later when we start to deal with some modern physical and biological theories of complexity.

The consideration about the inner structures of different systems is quite important, because it helps us to divide them into the proposed categories (i.e. simple, difficult, complex) a bit more easily, although it does not result in any exact definition. Certainly we will never be able to sort every system into to one of these "boxes". Our only intention is to get a general idea of *what* systems we are talking about when we mention complexity. Up to now we have reached the criteria as follows: a complex system is a natural system acting as one substance and it is indivisible without loosing some important features.

Of course the most typical example of complex systems are all living beings; designating such a system as complex one cannot make a mistake. The same is true for their parts (i.e. cells, organs, etc.) and, in the case of humankind, also for the many "products" of its creativity as well as inborn faculties (i.e. language, art, but also the most advanced computer programs).

To some extent the last category mentioned casts doubt on the part of our 'definition' of a complex system that states that it should be *natural*. But, is it possible to state about a computer program that it is natural? Probably not, however the answer is far from certain. The reason is that the most

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[41] In our treatise we shell however use this statement in the broader sense. By "alive" we shell rather understand to be open, to evolve, to be able to learn etc.

sophisticated computer programs are already so advanced that they overreach the abilities and knowledge of a man – their creator – and starts their own independent “lives” or existence. Now, we can reverse the question. Are they *artificial* in the proper sense of the world? It is a really difficult question to answer and since the issue is very new it represents a big task for philosophers to deal with. As far as we are aware of the results reached in this direction we unfortunately conclude that not much has been done in this field up to now.

4. Time evolution of complex systems

When we speak about the characteristics of complex systems we must not leave out of consideration their existence in time. It belongs to the very nature of complex systems that they encompass their own past, in other words, they have some kind of *memory*. Without some memory they would not be able to learn and to adapt themselves to the changing environment and they would never reach the level of complexity they have at present. Indeed time plays a crucial role in the description of complex systems and it cannot be eliminated from the theory, otherwise one could commit an unacceptable intervention into the matter of the known system.

Although this demand sounds quite natural, in reality it represents state of affairs that is rather strange for ordinary science. In most physical theories time is either not considered at all, or it is replaced by a parameter.

On the other hand, the concept of time has attracted people since always. One of the contemporary scientists, who has devoted all his life to study of this phenomenon is Ilya Prigogine. In the foreword[42] of the famous book written by Prigogine and Isabelle Stengers *“Order out of Chaos; Man’s New Dialogue with Nature”* (Prigogine 1986) Alvin Toffler says that already as a student Prigogine was surprised by the significant contradictions in the ways in which the science understands time. It is sufficient to name the Newtonian physics where the ontology of time is rather redundant. Within this physical

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[42] The foreword “Science and Change” (Prigogine 1986).

conception = time-instants are considered to be exactly the same (qualitatively), regardless of whether they are connected to past, present or future events. Moreover, the direction of time-continuation is also neglected, because the simple movements of physical bodies can be realized backward or forward without causing any significant influence on the system. Therefore, time in Newtonian systems is called “reversible”.

This situation changed significantly in the middle of the nineteenth century when thermodynamics was born; particularly the second law of thermodynamics. Time was put into the centre of scientific interest again.

The second law of thermodynamics (the entropy law or law of entropy) was formulated by Clausius and Thomson following Carnot's earlier observation that, like the fall or flow of a stream that turns a mill wheel, it is the "fall" or flow of heat from higher to lower temperatures that motivates a steam engine. The key insight was that the world is inherently active, and that whenever an energy distribution is out of equilibrium, a potential or thermodynamic "force" (the gradient of a potential) exists that the world acts spontaneously to dissipate or minimize. All real-world changes or dynamics is seen to follow, or to be motivated, by this law. So whereas the first law expresses that which remains the same, or is time-symmetric, in all real-world processes the second law expresses that which changes and motivates the change, the fundamental time-asymmetry, in all real-world process. Clausius coined the term "entropy" to refer to the dissipated potential, and the second law, in its most general form, states that the world acts spontaneously to minimize potentials (or equivalently to maximize entropy), and with this, active end-directedness or time-asymmetry was, for the first time, given a universal physical basis. The balance equation of the second law, expressed as $S > 0$, says that in all natural processes the entropy of the world always increases, and thus whereas with the first law there is no time, and the past, present, and future are indistinguishable, the second law, with its one-way flow, introduces the basis for telling the difference.[43] The progression of the universe cannot be reversed; in reality the universe is continuously getting older. So, time cannot be seen as reversible any more; only irreversible.

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[43] Later Eddington called this time tendency the “arrow of time”.

Alvin Toffler sees this situation as the limit point where science divided into two attitudes towards time. And this discrepancy has persisted in the modern physical theories, too.

One can mention, for example, the works of Einstein on space and time on the one hand and on the other hand the whole of particle physics – dealing with systems on the atomic and subatomic level – adopting time symmetry as one of its fundamental principles.[44]

The problem of the “ontology of time” is however much older. If we look deeper into the history thought we find that it has been a subject of academic disputations since the very beginning of man’s search for the truth about the world; to give their overview would demand an independent treatise. Since it is not our aim to deal with this problem in detail we restrict ourselves to only mentioning some of the many “Fathers of Science” and we will try to refer their thoughts to the complexity problem.[45] The first of these thinkers comes from a time when natural science and philosophy were one.[46]

Traditionally, if we want to speak about time we must start with Plato[47], who in his famous Dialogue *Timaeus* distinguishes between things that always exist without any origin, and things that are still originating and thus can never exist.[48] Despite the fact that the original context is slightly different – Plato actually speaks about the creation of the whole universe – we can find in this statement a confirmation of his deep insight into the process of originating (in modern terms we would say 'emergence').

In the foregoing text we already indicated that the continuous originating of new qualities, i.e. development or positive evolution, is one of the fundamental properties of a general complex system. A complex system

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[44] However, recent experiments carried out at CERN in Geneva and at Fermilab near Chicago demonstrated a clear evidence for violation of the so-called T symmetry in the observed decay rates for neutral K Mesons. It means that physics actually *does* differentiate between the forward or backward movement of time (*Science News*).

[45] We are well aware of the fact that these trials can be seen by some as anachronistic, incompetent and misinterpreting these famous thinkers. To some extent these objections are warranted, however we find the effort useful for obtaining deeper insight into the complexity problem – at least in the sense of inspiring for questions.

[46] Nevertheless, in more recent times one also finds some philosophers who could be considered to have been natural scientists (e.g. Aristotle, Descartes, Kant) and some scientists who were good philosophers as Newton for instance.

[47] Plato (cca 428-348 BC).

[48] *Tim*. 28

never finds itself in a steady state. In other words, its properties are never fixed; they are any different in every moment. And this process is continuous and smooth. Does this mean, however, that in accordance with the quotation taken from Plato's *Timaeos* that the true existence of complex systems impeached? At least it puts this problem in another light. Nevertheless, since the term 'existence' would itself need more detailed treatment we will close up this issue with the statement that even the existence of complex systems is not as evident as the existence of other "dead" things. Understanding this is intuitive rather than rigorous.

Another interesting observation of time can be found in Aristotle. According to interpretation of Leo Elders (Elders 1997: 56),

> Aristotle's time accompanies change that is continuous, which implies that time will show the structure of continuum. The continuum, in particular local movement, is characterized by a "before" and "after" which result from places traversed by the moving body. The "before" and "after" are found in other changes too, such as the alteration of qualities.

In our case the "before" is clear, for instance the state of an uninformed complex system, and "after" is the new state when the given system is already enriched by some information, i.e. it finds itself in a more developed state for it has learned something.

Elders continues:

> We attain to the concept of time when we notice a "before" and "after" in a movement. Apparently man must retain in his memory a starting-point and a later point in the process of change. In this way time is an aspect of the awareness man has of a change. If one perceives an instant as unique, one does not have an experience of time, for in this case one does not know that time has passed. At this point Aristotle introduces the definition of time as "the number of movement"[49]. With this expression he wants to say that time is based on a retaining or numbering and dividing. Thus time is what is counted in a movement.

Since, as we have already stressed, time itself is not a main subject of our treatise we shall try to reverse the problem. If we accept what Aristotle said about time, we can use it as a confirmation of our proposition that time cannot

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[49] *Phys.* 219b1.

be excluded from the description of complex systems. The reason is that all terms that play a role in Aristotle's text – e.g. continuous change, continuum, alteration of qualities, movement – are essentially connected with all complex systems. Thus, the simple reversal of the implication inherent in Aristotle's definition leads to a vital condition that must be considered if we are to try to deal rigorously with any complex system.

Another important personality in the history of science and philosophy was René Descartes[50]. From the many of his important concepts we would highlight is the one that has led to the distinction between the real duration of things and the human perspective of time; primarily because it probably had a crucial influence on Newton who was the founder of modern physics (cf. Sokol 1996):

> …the most important attribute of human knowledge is for Descartes certainty: the true knowledge is only such that its result is valid everywhere and at all times. Therefore, time must be excluded from the known reality. Certainty and evidence are however possible only in present, in a time instant.[51] Strictly speaking, one of the main tasks of metaphysics is to *replace time by a homogenous parameter*. The most important property of this parameter is arbitrary divisibility which then allows application of the mathematical approach. Time of the known reality does not have any content, it is not a cause and it does not assure any connection with what we know.

The part of the sentence above written in italics is of crucial importance. One can find its imprint in almost the whole of modern physics from Newton on. To replace time by a parameter certainly has far reaching consequences for the whole ontology of time. Since then has been 'time' regarded differently; for natural scientist and methodologists of science it lost much of its importance. However, this is not what we want to analyse now. For our part, we would rather try to reverse the problem again and look at what this new approach means for the study of complexity.

Of course it is true that classical science, which has adopted this understanding of time is usually not dealing with complex systems; it is not its subject. On the contrary, the new complexity sciences are mostly already well aware that they must use different methods than those of the mechanistic

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[50] R. Descartes (1596-1650)

[51] Cf. *Meditationes* V, A-T VII, 69 f.

sciences, hence to deal with time in the fullness of its meaning is rather natural for them. However, this is not always the case. There is a big part of science devoted to open natural systems at all levels, where the problem of time is still far from being solved. On one hand there is a strong demand for the mathematisation of all problems, on the other hand we already know that to put something into an equation is the same as to fix it up. Using hyperbole we can say that we must first “to kill nature” and then we can deal with it as an unchanging thing.[52] And this procedure is strictly prohibited when dealing with complex systems.[53]

The last two thinkers that we would like to mention here are Immanuel Kant[54] and Henri Bergson[55]. Kant firstly paid attention to the problem of time (according to Sokol 1996) in his Inaugural Dissertation in 1770. In the explanation of time that he gives in §14 of this work, the most important for our purpose is point 7 of this paragraph, where Kant says that “time is the absolute formal principle through which the phenomenal world originates”. One can find a slightly different view in his *Kritik der Reinen Vernunft* where it is said that time is nothing more than just a form of the inner opinion.[56] Time is neither objective nor real, but subjective and ideal basis of our external senses. The natural world does need time, but it is us – as humans – who de facto create it. Does this mean that time is not an attribute tightly connected with any real system? Kant answers[57] that the world either has or does not have an origin in time and this is not decidable.

A completely different understanding of time can be found in Bergson’s works, whose main idea was that everything is changing and stability is rather

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[52] As an example we can mention quantum mechanics, which works with operators instead of the quantities commonly used in classical physics. As yet, nobody has succeeded to introduce a time operator into the theory despite many people having tried to do that (cf. the theory of Lax and Philips, R. Newton, D. Rosenbaum etc.), for the possibility of expressing the time evolution of quantum systems is crucial in many cases. The classical task demonstrating this problem is to describe particle decay on the subatomic level.

[53] Of course, it is not possible to adhere to this strong demand for one hundred percent, because if we would keep this restriction in mind all the time we would never be able to formulate any theories, nor any models that are very useful for study purposes or applications. However, in this section we try to speak philosophically, which means that we must try to respect the nature of things as much as possible. Thus, we must stress again that a description of a general complex system that ignores time is not acceptable.

[54] I. Kant (1724-1804).

[55] H. Bergson (1859-1941).

[56] *KdrV* B68.

[57] *KdrV* A426-433.

an exception. One of his fundamental terms is 'duration' (*durée*) which he identifies with the real time. However, on contrary to Kant he does not consider time as “subjective”. For Bergson the sense cognition of duration is tightly connected to duration or “the inner time” of the universe that is the creative evolution (*L’évolution créatrice*), qualitative or “content” time. The Universe is developing, it has a future that remains open; its future is not purely an extrapolation of the past, it always brings something new.[58] And this is the view, which is very close to our notion of natural (i.e. complex) systems.

Moreover, when Bergson deals with the past he says, very simplified, that time is progressing like a snowball. In each moment it keeps its past within itself, thus with the ongoing progress the memory of the Universe gets more extensive and it follows that in the succession of time instants, each following instant is to some extent richer than the previous one. The universe learns, and this is exactly what we have said about complex systems. So, in Bergson one can see one of the important predecessors of the representatives of the “modern” approach to the world.

To bring this section to a close we can say that almost no “scientific”, “philosophical” or “psychological” time embedded in different theories describes the full ontology of the “being-in- time” of open evolving systems. To keep to the natural sciences, the situation is hardly any better in biology than it is in physics, because biology deals with living systems where one simply must factor the concept of time into the theory; particularly, because ageing is one of the most fundamental laws of life, and cannot be expressed without considering time.

Aside from the question of what time really is, we conclude that time is a fundamental aspect of all complex systems and that one must always keep it in mind. Complexity is subject to evolution, as everything in the world is. Actually an increase in complexity is the main indicator of positive evolution. As a consequence, *no* physical theory or model that neglects time, or only considers it as a parameter going in both directions, can be suitable for a true description of complex systems. It is a conclusion of great importance that would make many scientists unhappy, but it cannot be avoided.

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[58] That is why he uses the term „creative evolution“.

Another important notion is connected to the concept of time – *causality*. According to this principle everything has its cause. It means that nothing can originate from nothing-ness; things only originate from something. A storm originates from a defect in the earth's atmosphere, a plant grows from a seed, a child is born from the joining of its two parents' gametes, a language must be spoken by someone and a novel was certainly written by someone.

Following the concept of the time arrow we can add that this *something*, i.e. the cause, always precedes its consequence. However, almost nothing in the real world is so simple so as to allow decoding proper causal relations. Not all things have so simple a history as those we listed above. Sometimes history goes so far back in time that nobody is able to reconstruct it again. For example nobody knows how and by whom exactly the big statues on Eastern Islands, or the Stonehenge in England, were built; their origins are already forgotten by humankind. Something cannot be remembered if it is older than human memory itself. This is the case with the origin of man from his animal predecessors or the creation of our solar system.

Quite often we cannot uncover the course of a situation, although the history can be quite short. Aristotle already pointed this situation out and said that in real situations one usually has to deal with a vast number of *causal chains* that can be very tricky and richly intertwined.[59]

However, despite the fact that the true cause often stays hidden to our eyes the principle of causality assures us that this cause *does* exist and it is knowable at least for the members of the family of Daemons.

Even though we cannot say properly what *is* a complex system, we can say now what it is *not*. An inert system in the general sense of the word is not complex though in the past it could have been. A dead butterfly is still a very "complicated thing" but not complex as we understand this term. The reason

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[59] Cf. the well-known story about a thirsty wanderer who is taking a rest near the well and a thief who is running away from the scene. These two meet and the wanderer is killed "by chance" by the thief who thinks that he is pursuing him, and who then continues on his way. If we come across the final scene – the dead man near the well – and we know nothing more about the past of these two men, we can easily conclude that this all happened just by chance. But, according to Aristotle, this would not be true. Both events have their causes: one man came to the well because he had been thirsty, the second one because he had been running away. This is an example of only *two* interacting causal chains. But, if we want to fully understand the whole "life" of any complex system we would have to deal with many similar chains, which is beyond our abilities.

is that its parts do not mutually interact any more. The only attribute of complexity (besides the enough big number of its components) that it has is “movement in time” – in the air it decomposes slowly, and after some time it completely ceases to exist.

If we imagine the situation that the dead butterfly is taken and mummified – as the Egyptian Pharaohs -, i.e. protected against all influences coming from the environment, it looses also the last feature of complexity and turns into “only” complicated system. The parts it is composed of are theoretically decomposable and compoundable without loosing any fundamental attribute.

Now imagine a complex computer program running on a complicated machine. It is not living in the proper sense of the word but it bears the necessary characteristics: it is composed of a huge number of mutually interconnected parts and it evolves in time. If the hardware breaks down, the program stops as well, and the complexity is no more.

Without time there would be no complexity. Or, conversely the existence of complexity represents a basis for the existence of time. Complexity is an accidental attribute of physical, biological, etc. systems and time is a measure of their movement. They are strongly interconnected and they cannot by separated. Time without complexity would be a “dead” parameter; complexity without time would dissolve into “complicated-ness”.

5. Complexity means structures with variations

Imagine the world being as one amorphous amoeba without any inner structure. There is no ground, no ether, no trees, no people and no sky with any stars, only a homogenous “something” that exists in time without any change. It is not a nice picture, is it? Now imagine that at the opposite site of the Universe there is another world that is conversely totally chaotic. It is a boiling soup of the smallest elements spinning in chaotic movement. There are no rules for them how to behave, no plans for their future existence. Everything is just a matter of instance and what has been once realized never happens again. Fortunately, our world is different. It is a system with a structure. It is neither homogenous, nor chaotic. If this were the case then there would be no variations in nature. Not only the world would be composed of different homogenous *parts* but even the world *itself* would be homogenous as a whole because every complex system is to some extent a part of some meta-system continuing ad infinity (to the whole-ness of the universe).

The same is true for all complex systems in general; if there were no particular structure within the complex systems then their functioning would be strictly limited. We would not have legs to move with, lungs to breathe with, a brain to think with and hands to write with. Structure brings forth the possibility of task distribution in the given system that allows it not only to perform operations more economically' but also to be able to solve much more tasks.

Similarly, if complex systems were chaotic, then they would not be able to perform any sophisticated activity either, because there would be no connecting strength that would lead the system's activity.[60] One could even say that there would be no activity within the system at all. Every element inside the system has its own activity in as far as one can denote chaotic behaviour as an "activity".[61] However, there is no way in which to synchronize these particular activities and so to enhance their effects.

So, the existence of some structure within the complex system seems to be a necessary condition. But how should we understand the term "structure"? The meaning of this word would perhaps not be difficult to understand, because it is familiar to all of us. The problem, however, emerges when we start to ask about the origins of a structure, i.e. the mechanism of its coming into being.

For instance P. Cilliers distinguishes between two ways of understanding the notion "structure" (cf. Cilliers 1998: 99): structure as something that exists in an *a priori* fashion, and structure as the *result* of action in the system, with an inclination to the later. Some structures have always existed[62] for example, the crystal lattice of the common salt (NaCl), the skeleton in vertebrates or our solar system. Other structures come into

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[60] The matter of chaos is much more difficult than we have hinted at and therefore one of the next chapters will be devoted to this topic.
[61] For the word 'activity' gives the feeling of some hidden order in behaviour; of some inclination and goal where the 'activity' should end.
[62] Properly speaking we should say that these structures exist as long as their bearers themselves do.

being as a result of the movements of some entities. For example, molecules of water come together and create sc. liquid crystals, or people with the same political opinions create a structured political party. Such structures can be labelled as "secondary", because they are composed of elements that possess some inner structure themselves. Molecules of water, for instance, are composed of two atoms of hydrogen and one atom of oxygen. The human body is also structured according to a given plan, much more sophisticated than in the case of water molecules.

While the "primary" structures belong to subjects per se and essentially (for they are parts of their very nature), "secondary" structures are different. They can originate, but often they do not have to. This process is voluntary to some extent, depending on conditions. Such structures also usually do not last forever, but cease to exist sooner or later.

By creating the secondary structures the process does not, however, finish; there can be structures of structures continuing into infinity. Moreover, some of them exist for the sake of the others; all of them exist for the sake of the whole. They are not ordered into a line, but make hierarchical successions in all directions. Here we meet with *hierarchy*, and this is the reason why hierarchy plays such an important role in the study of complex systems.

When we return to the issue of complex systems we can say that their structures also differ according to the level of complexity that is shown by the particular systems. Moreover, the structures evolve in time in the same manner as the whole system. Simple complex systems can be characterised by only one structure, but more sophisticated systems can posses more structures and patterns that can additionally cease to exist in favour of new ones. The lifespan of these structures can vary considerably as well.[63] These structures can be also intertwined in non-trivial ways. All of these facts create serious difficulties for attempts at modelling complex systems.

The structure of complex systems is asymmetrical. Let us illustrate this using the example of a human body. The fundamental element of a human

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[63] The study of the spontaneous emergence of new structures and patterns has its roots in non-equilibrium thermodynamics. In states far from equilibrium new types of structures can emerge. Under "strongly non-equilibrium" conditions thermal chaos can change into order. These new structures are called "dissipative structures" (Prigogine, 1984).

body is the cell. The cell is not, however, the smallest component of the body, because it is in itself a composed object. It consists of different organelles that guarantee its living functions. The organelles are less complex than the whole cell and their operations are ordered according to the cell function.

The next constituent of human body is tissue, which is made up of cells. On this level individual cells appear to cooperate, and their individuality is wiped out for the sake of the whole unit. This process continues, via organs and systems of organs, to the body as a whole. But this is not the only hierarchical succession one can recognize in the human body. The systems of organs share the same species-classification, even though they are hierarchically variant. The privileged position belongs to the nervous system, which coordinates and rules over all of the activities within the body. But the nervous system is not the final hierarchical element; in humans this is their mind.[64]

A hierarchical structure is very advantageous for systems, because it allows them to make the best of evolutionary opportunities and to establish unambiguous routes of communication. Thanks to the inner division of a system its parts can evolve quasi-independently and each of them can find the most beneficial way to develop. For example, the human hand that has its own evolution history, ordered according to the tendency of the whole. Although it was certainly connected to the evolution of other parts of the human body – e.g. the shape of the skull – it could, to some extent, go its own way. Information transfer is also much more economical and profitable in systems with structure, because different tasks can be ruled from different centres. If one of these centres is damaged, it does not necessarily cause the end of the whole organism.[65]

Since structures within complex systems are subject to evolution, they are not permanent or fixed in their being, either. They change in time and interpenetrate each other. However, this process cannot be considered to be

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[64] Despite the fact that the problem of man's immateriality has been a subject of passionate discussion – both philosophical and scientific – without any hope for a final solution, we dare to propose that thought is the highest form of activity one can find in the universe.

[65] This issue has found its application in some modern management theories on how best to rule an enterprise that get inspiration from nature. The enterprise is considered as a hierarchically structured organism and the information routes in the enterprise are created to follow the natural routes as present in an organism.

accidental, but results from other processes, learning or adaptation, for example.

It is not possible to represent any complex system as a multi-layered object with a multi-layered structure; the reality is much more complicated. Hierarchical structures emerge on all levels (as we saw when we spoke about the human organism) and moreover there is active cross-communication between them. How to study such intricate systems and what the possibilities of modelling them are, will be elaborated on in chapter V.

6. Modes of complexity

Thus, as we saw in the foregoing, there is no agreed upon definition of complexity. What we do know, according to Nicholas Rescher (1998: 8), is that complexity is the opposite of simplicity.

> The latter is a matter of economy, the former of profusion. Simplicity represents economy and orderliness in a thing's make-up or operations; complexity is determined by the extent to which chance, randomness, and lack of lawful regularity in general is absent.

But, the issue is not so simple. A system cannot only be more or less complex, but is also complex in substantially different ways, as is indicated in this chapter.

According to Rescher, one can distinguish between three fundamental modes of complexity: epistemic, ontological and functional. He describes them as follows (Ibid: 9):

Epistemic Modes

Formulaic Complexity

1. *Descriptive complexity*: Length of the account that must be given to provide an adequate description of the system at issue.
2. *Generative Complexity*: Length of the set of instructions that must be given to provide a recipe for producing the system at issue.
3. *Computational Complexity*: Amount of time and effort involved in resolving a problem.

Ontological Modes

Compositional Complexity

1. *Constitutional Complexity*: Number of constituent elements or components.
2. *Taxonomical Complexity (Heterogeneity)*: Variety of constituent elements: number of different *kinds* of components in their physical configurations.

Structural Complexity

1. *Organizational Complexity*: Variety of different possible ways of arranging components in different modes of interrelationship.
2. *Hierarchical Complexity*: Elaborateness of subordination relationships in the modes of inclusion and subsumption. Organizational dis-

aggregation into subsystems. Here the higher-order units are. For this very reason, always more complex than the lower-order ones.

Functional Complexity

1. *Operational Complexity*: Variety of modes of operation or types of functioning.
2. *Nomic Complexity*: Elaborateness and intricacy of the laws governing the phenomena at issue.

In common and simplified language we can say that the mentioned modes of complexity represent three different viewpoints: The first one – formulaic – expresses how we *speak* about complexity, how we *describe* it and what method we use to*solve it*. Ontological Modes touch on the very nature of complex systems. They speak about its inner structure – about the *number* of its constituents, about their *kinds* and about how they are *organized*. The third mode of complexity – functional – concentrates on the question of how complex systems *operate* and how they *behave*. If the Complexity Daemon were able to fulfil all of these criteria, he would be able to say everything about the given complex system, and to speak about it in a way that other people would understand.

Unfortunately, since we are not Complexity Daemons, we do not have any choice other than focussing on some particular aspect of complexity and try to uncover something of its wholeness every time we study it. It is natural that different people and different scientific disciplines pay attention to different modes of complexity. The epistemic modes are certainly used in the natural sciences; ontological modes are the domain of philosophy; functional modes are the subject of interdisciplinary studies.

From the point of view of most “exact” sciences the most fundamental form is perhaps *descriptive complexity* [66] and it is in this sense that N.

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[66] One sort of formulaic complexity is articulated in the idea of the Russian mathematician Andrei Kolmogorov, for example, who proposed to measure generative complexity by the minimal length of

Rescher makes his distinction. Complexity is the inverse of simplicity and the more elaborate the description of one item in relation to another, the more complex it is.[67] Consider a following example: we have two sequences

(1) 121212121212121212…
(2) 123456123456123456…

It is clear that the former is less complex than the latter, both with regard to composition and structure. The first group has only two components (1, 2) and the second has six (1, 2, …6). Moreover, these two sequences also differ in their generative complexity, since the first one can be reproduced by simpler instructions than the second.[68] On this basis, random structures such as the "snow" on TV screens or the pure noise of radio static are far more complex than any of their more orderly congeners, since in describing a strictly random series, one has to make a separate specification for each and every component involved.

Perhaps the most interesting example is the computational approach to complexity. It is matter of operational/functional complexity with regard to information management in the particular domain of problem solving. The idea can be represented by a simple equation $C = P \times t$ where P is a measure of the power of the information-processor at issue, and t is the time required for its deployment in the problem-solving context at hand.

Ontological modes of complexity are fundamental when one wants to grasp the nature of complex systems; to talk of them "per se". *Constitutional complexity* is a rather "special thing", since it is expressible only in vague terms and expressions such as "few", "many", "less than", "more than", "enough", etc. The reason being that it is not possible to determine the number of constituent elements of any complex system.

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an instruction-program for generating a sequence, using standardized process such as a universal Turing machine – see chapter IV.

[67] The problem of describing complexity will be discussed in greater detail in chapter VI.

[68] "Endlessly repeat the group 1-2" x "Endlessly repeat the group 1-2-2-4-5-6"

Compare, for example, a cell, the digestive system of man and the whole living body.[69] They certainly do differ in the number of their constituents, and we can rightfully assume that this number will increase, following the same sequence. However, the only thing we can say with certainty is that the digestive system is composed of more components than an individual cell, and that the whole body is composed of more components than both a cell and a digestive system. But nobody is able to tell the exact number.

The situation becomes a bit simpler in the case of *taxonomical complexity* where we pay attention to whole groups of constituent elements. By specifying the kind of components we are interested in, we significantly reduce significantly. We can modify our previous question, for example, to the form: “How many cell nuclei are contained in a cell, digestive system and body?” Now it looks better, because we can give a definite answer to at least one part of this question: “One cell contains just one cell nucleus”. This is without doubt a kind of progress, but as much as one would think. In the second case – the digestive system – we are already lost again. We cannot count the number of cell nuclei, because we do not know the number of cells that constitute this system. How successful one will be in describing the taxonomical complexity strongly depends on the criterion one chooses for defining the ‘kinds’ one is interested in.

The vision of the theoretically possibility of “measuring” taxonomical complexity has even entrapped some scientists to use it for evaluating organic complexity in biology. J. T. Bonner, for instance, proposed that organic complexity should be measured simply as the number of different cell types in an organism.[70]

As we have already shown earlier, a complex system that embodies subsystems can be organized either *hierarchically* through subordination-relations among its elements, or *coordinatively*, through their reciprocal

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[69] At this point Rescher suggests other examples, namely, tricycles, automobiles and jet aircraft. But, we stated in the foregoing text that these are examples of ‘complicated’ systems not complex systems. Since we want to keep the line of distinguishing between these categories clear, we will use more suitable examples (from our point of view) in the following paragraphs.

[70] Bonner, J. T. (1988) *The Evolution of Complexity*, Princeton, NJ: Princeton University Press; Cf. (Rescher 1998: 11)

interrelationships. A government or an ant society is an example of the former kind, while an economic system or a single biological organism illustrates the latter. In addition, the intricacy of arranging components can be influenced by many factors; one of the basic ones is the difference between two- and three-dimensional structures.[71]

Highly complex systems generally tend to exhibit a hierarchical structure. They consist of sub-sectors that have sub-sectors of their own. As an example we can look at the sequence: galactic clusters – galaxies – stars and planets – macroscopic physical objects – molecules – atoms – subatomic particles, or: living animal societies – individual organisms – cell organs – molecules. Such hierarchical structure is mostly *functional* and in all cases it is *structural*.[72]

Functional complexity takes two forms: it can be either *operational*, displaying dynamical complexity in the temporal unfolding of its processes, or *nomic*, displaying a timeless complexity in the working interrelationships of its elements. The former we can illustrate using the example of the lifestyle of primates, which is certainly much more complex than the lifestyle of snails. As an analogy of the latter form we can introduce the example of steam engines, which are more complex in this manner than pulleys. However, neither one of these two examples is a typical representative of a complex system – again, according to our division they are both only complicated. With regard to, the more degrees of freedom a system exhibits in its operations and the more versatile it is, the more operationally complex it is inevitably going to be.[73] An automobile's movement, for example, has two degrees of freedom (direction and speed) but an aircraft with its ability to change altitude has already three. Correspondingly, the latter requires more information to be understood and more elaborate control to rule its operation. Operational complexity is thus closely bound up with other kinds of complexity (Rescher 1998: 13). With increasingly complex machines, for example, we require larger manuals when

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[71] As an analogy one can use the example of comparing jigsaw puzzles with their two-dimensional arrangements, with LEGO blocks with their three-dimensional modes of assembly.
[72] Cf. Simon, H. A. (1981) *Science of the Artificial*, 2nd. ed., Cambridge MIT Press, pp. 116-117 and 195 ff.
[73] Cf. Popper, K. R. (1959) *The Logic of Scientific Discovery*, New York: Basic Books, pp. 139-140.

it comes to construction and maintenance. And the “operating manual” for increasingly complex organisms will exhibit the same feature.

With regard to *nomic complexity*, it is clear that the more complex a system is, the more elaborate its law-structure will be. And here chaos represents an extreme, for chaos is not an absence of laws but involves a mode of lawfulness so elaborate so as to render a system’s phenomenology cognitively unmanageable in matters of prediction and explanation.[74]

It is important to note that the different modes of complexity do not necessarily exist together. In theory at least, they can go their separate ways. For example, a human corpse is structurally complex but functionally much simpler – i.e. inert – as Rescher argues. On the other hand, functional complexity does not necessarily require compositional complexity. A typewriter with a modest number of keys can produce an infinite number of texts. Moreover, even a world that is finite in the structural complexity of its physical constituents may well exhibit a functional complexity that involves a “hierarchy of nomic orders” in its lawful operations, with an ongoing sequence of levels of ever higher-order laws.

We devoted this chapter to complexity itself. Since it is very difficult to define it – one can say that it is almost impossible –a careful treatment of this issue was necessary. We started our considerations from the presupposition that something like complexity – despite of the vagueness of this term – *does* exist, and that it therefore must be knowable (at least to some extent).

Searching for a thing the existence of which is not evident is nothing new for a science. An archaeologist might find the mention ofan unknown temple written in old scrolls and after few years of hard work he might succeed in finding its ruins. A palaeontologist might be missing one animal species in the evolutionary chain, and hopes to find its remains or traces one day. A particle physicist studies a nuclear reaction and observes that one as yet unknown elementary particle must be involved in this reaction since his equations do not work without considering it. Finally this particle might also be found. In the case of complexity the situation is slightly different, however. The reason is that there is no hope of finding ‘complexity’ in itself one day. Why

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[74] The reader will find more on this topic in chapter III.

not? For complexity does not exist by itself. It is an attribute of a subject; philosophically speaking it is the predicate of a subject. That is why we had to change the approach to the problem of ‘searching for the unknown’ to ‘searching for a known that possesses the attribute of complexity’. Therefore, a substantial part of our treatise was devoted to characterising systems that can be considered to be complex. Roughly speaking, we finished this chapter at the moment when we reached some knowledge about *what* complexity is.

If we already know what we are looking for, there is a bigger chance of discovering it. In the next chapter we are going to focus on another question that naturally follows from the first one: *Where* is complexity? We will try to find out where one can find complexity.[75]

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[75] Here the adverb ‘where’ has a broader meaning than just a question of place. The right answer we are looking for won’t only have the dimension of “at what place”, but will also touch on quality.

III CREATING COMPLEXITY[76]

Claus Emmeche starts his brilliant paper (Emmeche 1997: 2) by characterising complexity as concerning “systems with more parts, different parts, and special relations between various kinds of parts, forming a structure which must be described on several distinct levels of organisation and as involving entities with emergent properties”. All these terms – complexity, parts, relations, structure, and organisation – have already been analysed in the previous chapter, except for the last one: emergence. Emergence refers to the process where something new or as yet unknown comes to the fore. Of course, “an old friend” can also suddenly emerge somewhere, however, the important fact about emergence here, is that at one instant an object is *not*, and in the following one it *is* there. In this chapter, we will consider mainly this sense of the word ‘emergence’, expressing the *originating of something new*; the arising of new features of complex systems. Of course, if we have a “what” in connection with such originating, we should also ask “how” and “where”.

One of the possible answers to the question “Where does complexity emerge?” is: “Somewhere between the states of chaos and order”. Here we use the term ‘chaos’ in the common sense of the word, rather than the purely scientific sense.[77] We are well aware of the fact that ‘chaos’ in physics and the computer sciences is a strictly defined term, with an exactly given meaning.[78] By using this word we do not mean anything other than simply

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[76] Of course there is one more question of the great importance, i.e. “why”, but since it is a purely philosophical matter we shell leave it aside for the present.

[77] WorldNet Dictionary gives following definitions of the term ‘chaos’: i) (Greek mythology) the most ancient of gods; the personification of the infinity of space preceding creation of the universe; ii) the formless and disordered state of matter before the creation of the cosmos; iii) a state of extreme confusion and disorder.

[78] A *computing dictionary* says that: “Chaos is a property of some non-linear dynamic system which exhibit sensitive dependence on initial conditions. This means that there are initial states which evolve within some finite time to states whose separation in one or more dimensions of state space depends, in

extreme disorder – in opposition to *order*; the state of a system where no rules and laws matter a state that is completely unpredictable and indescribable. (In this domain even the members of the Daemon`s family are helpless.) At this point it is necessary to introduce the discrepancy between our understanding of the term ‘chaos’, and the understanding in physics, since within the latter there is some determinacy in connection with this word – (see previous footnote).

The edge between the extreme disorder and extreme order represents the place where structures originate. And structures are the basic building blocks of all complexity, since every complex system is by definition a *system with structure*. It does not matter if systems are ordered in space and random in time, or ordered in time but random from a space point of view. Among such structures one can sometimes find a few “individuals” that are able to multiply, compete with each other and evolve according to the laws of natural selection. They are studied by scientists from all scientific disciplines in the hope of finding general adaptive mechanisms that would help scientists to understand such problems as the functioning of the human immune system or the dynamics of fluids better.

Joseph Ford said: “Evolution is a chaos with backward binding” (cf. Gleick 1987: 318). And the ability to evolve is indisputably a very important feature of every complex system. Moreover, it is the element that leads to complexity. The universe is represented by randomness together with diffusion, but randomness with direction can bring forth a surprising intricacy. “God plays dice with the Universe” Ford answers the famous assertion by Einstein. “But, these are dice with lead embedded within them. And this is the main goal of today’s physics, to find the rules according to which the lead was embedded, and how we could use it for our own benefit.”

What the mechanisms of creating complexity are, is a subject of everlasting scientific discussion. Up to now interesting theories have been proposed, the theory of self-organized criticality, for example. Proponents of

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an average sense, exponentially on their initial separation. Such systems may still be completely *deterministic* in that any future state of the system depends only on the initial conditions and the equations describing the change of the system with time. It may, however, require arbitrarily high precision to actually calculate a future state to within some finite precision.”

this theory are convinced that nature organises itself spontaneously, and that nothing other than purely physical laws are responsible for this. When some particular conditions are fulfilled, organization is an inevitable product of the world’s course. Nevertheless, how and why these dramatic changes to the system’s complexity happen is still a mystery.

Another promising approach to the complex reality relates the macroscopic features of “big” complex things with their microscopic components, e.g., the jaguar with a quark, as Murray Gell-Mann does in the title of his famous book (Gell-Mann 1994). Of course - if one exaggerates - a jaguar is composed of quarks but so is a man or a table. Can the quantum mechanical laws relevant to quarks explain the jaguar’s temperament, or the pattern of dots of its fur, at least? This can hardly be the case. Or are these organizing principles perhaps at work at the mesoscopic scale? ThisI is another theory, but who knows?

There are many other powerful physical theories, besides quantum mechanics that deal with this problem (e.g. the theory of relativity). Supposedly one of the oldest is thermodynamics; especially its second law introducing a quantity called *entropy*[79] (S), which is a measure of disorder. The second law says that *the entropy of the universe increases*. An increase in (overall) disorder is therefore spontaneous. If the volume and energy of a system are constant, then every change to the system increases the entropy. If the volume or energy changes, then the entropy of the system can actually decrease. However, the entropy of the universe does not decrease. This argument is often used by creationists who believe that the second law of thermodynamics does not permit order to arise from disorder, and therefore that the macro-evolution of complex living things from single-celled ancestors could not have occurred.[80]

The second law of thermodynamics is frequently applied in many other fields; it is held responsible for the disintegration of societies, for economical decay, for the collapse of morality etc. (cf. Gleick 1987: 312). But, if one looks

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[79] See p. 42.

[80] However, it is only the *overall* entropy of a complete, or *closed,* system that must increase when spontaneous change occurs. In the case of spontaneously interacting *subsystems* of a closed system, some may gain entropy, while others may *lose* entropy.

around, one observes a completely different reality. One sees surprising intricacy and the beauty of existing complex things. How is this possible? Although we know the physical theory, an exhaustive answer is still far from being clear…

1. Emergence, anticipation, and adaptation

R. Rosen said (Rosen, http. 1997) that ‘emergence’ and ‘anticipation’ are two different aspects of complexity. But, how should we understand these two notions?

Emergence means coming into being, becoming, beginning of something new. It is a process. Anticipation, on the other hand, is the end where we start. It is a law or a principle according to which a system evolves, as it ‘anticipates’ the end to be reached. It is a kind of order within the system, which allows it to determine a present change in accordance with a prediction of the future state that will follow from the system’s regularities; as Rosen calls it, a predictive model. While anticipation is incorporated into the system, emergence accompanies its duration in time.

From two merging gametes a new life is born; a new individual *emerges* from just two cells. The newborn human body forms new structures day by day. At the beginning the changes happen more quickly, but as life goes on they are slower and slower. However, they never stop. After the rapid growth of the body, a time of apparent stagnation arrives, followed by changes that indicate aging. At each stage of human life, not only quantities but also qualities emerge. A human individual grows, matures and learns; he or she knows their environment and *adapt* themselves to the actual conditions under which they live. Although each individual human life is original and in detail unpredictable something in it is fixed: its tendency toward an end, via inescapable biological determinations. All people must start their existence as children, then they become adults and, if everything goes naturally, they die when they are old. It is a model hidden in every man and rooted in his very nature. Therefore, a man can be considered as an *anticipatory* system, for the course of his being is, to some extent, determined. We are children in order to be adults; we are born in order to die.[81] Complexity itself is an emergent property; the authors of *Frontiers of Complexity* (Coveney 1995: 344) even assert that:

> Life is also an emergent property, one that arises when physicochemical systems are organized and interact in certain ways. Similarly, a human being is an emergent property of huge numbers of cells, a company is more than the sum of its pens, papers, real estate, and personnel, while a city is en emergent property of thousands or millions of human beings.

Complexity is not present in the universe from its very beginning; it 'emerges' in the course of its being in time. "How?" is still a question that we cannot answer. Can we ever hope to understand such highly emergent properties? According to the authors the answer does not have to be purely negative; it is a matter of the fact that:

> Contemporary philosophy has tended to shun the notion of emergent phenomena, for the scientist, complexity places renewed emphasis on interdisciplinary research, in the Renaissance style, and underlines the symbiosis between science and technology».

The complexity of the world we live in is the result of the interactions of the many parts that the world is composed of, on many scales. New features in the world emerge mainly while moving from one scale to another (Vicsek, 2002).

> The science of complexity is about revealing the principles that govern the ways in which these new properties appear.

According to D. C. Mikulecky (Mikulecky 2001), it is important to distinguish between *two kinds of emergence*. The first one is the emergence of new things by some evolutionary process, while the second is "the discovery of attributes that were always there, but were invisible to the Newtonian Paradigm".[82] The latter mainly points out the fact that with the birth of a new science of complexity, seemingly new attributes of systems were

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[81] In Sein und Zeit Heiddeger calls this sad reality "being-toward-death" (*Sein-zum-Tode*).

[82] This is based on the author's conviction that "Complexity is the result of the failure of the Newtonian Paradigm to be generic" (Ibid.). He affirms equality of all of the "hard sciences" (a model for all sciences), defined by using Cartesian Reductionism, the machine metaphor and a broader application of Newton's laws of motion (called the "Newtonian Paradigm" here).

recognized.[83] Thus, as Mikulecky says, emergence can be the result of the limits of a dominant formalism, and might even be associated with error of a certain kind. This is important, since it allows us to distinguish "between truly differing forms of emergence". On contrary, there are many natural phenomena that can, without any doubt, be described as emergent. Mikulecky proposes developmental biology and evolution as examples. In both cases the system involved changes profoundly and new properties and structures are generated from existing ones. Moreover, it is not possible to model either of these in the Newtonian Paradigm, so they also fit his category of "emergent property". To sum up:

> The lasting aspect of the emergent nature of these systems is in their own change, not in the need for new ways to describe them.

The emergence of new entities on a higher level implies the existence of *downward causation* (Emmeche http.; Küppers 1992). This is, however, a very contentious statement,[84] since the proposition "the whole of nature is causally closed", which immediately follows when we add downward causation to the natural bottom-up causation we are familiar with,[85] is difficult to interpret, both scientifically and philosophically.

In science, and particularly in physics, there is a strong belief in sc. micro-determinism stating that everything follows from the laws of the micro-world.[86] If this is the case then causation in nature is clearly bottom-up, and downward causation is either a violation, or it can be complementary to the former as its reverse image. However, recent acquaintances from complexity

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[83] Cf. the discovery of superconductivity in 1911 by H. K. Onnes etc.

[84] According to C. Emmeche one of the strongest arguments against the notion of downward causation is as follows: "if e.g. a mental state, through downward causation, changes a neural state in the brain, then we could see this as violating the neuro-physical causal closure of the system on the micro level, where one physical state (that corresponds to the neural state) should be a sufficient cause for the next neural and physical state, without further intervention from 'non-physical' (mental) causes (cf. Kim 1993)." However, the crucial point in this issue is to make a clear demarcation between "system" and "state".

[85] The ordinary bottom-up causation is a fundamental principle of all reductionistic science.

[86] We can broaden our family of omniscient Daemons with a new member – MicroDaemon. He is the child of the well-known LaPlacean Daemon, who has adapted himself to demands of a modern science and is specialized in the micro-world. Of course, he does not know more than his father, he has only taken over one part of his job –l to know all about the behaviour of micro-particles and waves and strings etc. (about all that can be considered to be the last elements of reality when going downward) and on this basis make predictions of the behaviour of any "bigger" objects. (We use quotation marks because at this level even the notion of size is very vague).

studies as well as from the quantum mechanics itself indicate that the world's reality is much more intricate than has been thought, and that simple micro-determinism probably won't be able to satisfactorily explain all its aspects. The modern approach of today emphasizes the necessity of choosing a particular frame of description and particular observables to understand complex phenomena, as Emmeche stresses.

In the case of philosophy, downward causation represents a true problem for ontology, because it allows only strictly efficient causation[87] and efficient downward causation surely leads to contradictions (Emmeche: http.; cf. also Emmeche 1999)[88] Nevertheless, Emmeche proposes a way to bypass this difficulty, by shifting to *semiotical causation*, which is different, for it involves other causal modes, namely material, formal and final causation. In addition Emmeche proposes three versions of downward causation, each with distinct ontological assumptions:

> In *strong downward causation*, an entity or process at a higher level may causally inflict changes or effects on entities or processes on a lower level, and the higher level entity is considered to be substantially different from lower level entities. The organizational aspect is a necessary, but not sufficient condition of the higher level entity: By its emergence, an ontological change in substance takes place. Thus, the higher level is held to constitute its own substance; it does not merely consist of its lower level constituents (this could be called constitutive irreductionism).
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> With *medium downward causation* it is not allowed for higher-level phenomena to directly influence directly lower level laws. The higher-level entity, such as a cell or a psyche, is a substantial phenomenon in its own right, and this entity acts as constraining conditions (a kind of formal cause) for the emergent activity of lower levels. The higher-level states that are already realised, are constraining conditions for the coming state.
>
> In *weak downward causation* the higher level is seen as an organizational level (not a substance), characterized by the pattern, the structure or *form* into which the constituents are arranged. The higher level entity, a biological cell for instance, *consists of* entities belonging to the lower level (constitutive reductionism). This is not a physical reductionism; the forms of the higher level are believed to be non-reducible

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[87] Let us now remind ourselves of the Aristotelian theory of causality. Aristotle saw four causes for all things: material, efficient, formal and final causes. We can illustrate this with help of the following example: an artist makes a sculpture. Then the material cause is the marble and tools he uses, the efficient cause is the artist himself, the formal cause is the plan he has in mind and the final cause is the sculpture itself with the purpose for which it is being made.

[88] If we stay with our previous example this statement is clear: the sculpture as the cause of the existence and work of the artist is an evident logical non-sense.

> (form realism). It does not interpret boundary conditions as constraining conditions; rather, the higher-level form can (in terms of the theory of dynamical systems in physics) be seen as a stable or chaotic attractor in a phase space, where the individual states (points in the state space) of the system is given by the configuration of the system's lower level entity properties and the dynamical equations that rule the time evolution of the system».

However, even in the weakest form of explanation the notion of emergence always clashes to some extent with the classical world-view. A few decades ago one would have said that it is something philosophically mysterious, as well as scientifically unacceptable. Nevertheless, recently this situation has completely changed. The reason lies mainly in the widespread acceptance of relativism and perspectivism (Emmeche: http.). Currently, the "emergence of irreducible new properties that constitute their own level of explanation or phenomenology is in harmony with the post-modern outlook".

As mentioned above, downward causation is also strongly connected to the second term we introduced at the beginning of this chapter, i.e. *anticipation*. In an interview (Rosen 1997: http.) Dr. Robert Rosen was asked if anticipation was an emergent property as well. He answered: "In general, I would say it is an emergent property, but that's another aspect of their behaviour… Anticipation does have emergent aspects." But what does 'anticipation' actually mean? Rosen devoted a whole book, entitled *Anticipatory Systems* (Rosen 1985), to this issue, where he uses the term in the sense of "style of control". Anticipation means the existence of a predictive model of the system within a particular system, and using the system's predicted future behaviour to modify its present behaviour in a desired way. However, in an earlier paper (considered to be a fundamental work in the field of anticipation) one can find a definition that is a bit more comprehensible (Rosen 1972: http.):

> An anticipatory behaviour is one in which a change of state in the present occurs as a function of some predicted future state, and that the agency through which the prediction is made must be, in the broadest sense, a model.

An even more simple definition, also coined by Rosen, and repeated by Heinz von Foester[89] reads as follows:

> An anticipatory system is a system whose current state is determined by a future state. I.e., the cause lies in the future.

In his already classical but brilliant talk about anticipatory systems (Rosen, http. 1972) Rosen proposed some particular examples: He starts with human behaviour, which he considers to be typically anticipatory (in contrast to purely reactive, as is often proclaimed by reductionistic science). If a man meets a bear on his road, he starts. Why? Because he can anticipate what can happen. The mechanism of this man-bear interaction is not simply the reaction: bear = dismay. More accurately, it is a whole set of images that are running through the man's mind, showing him as the bear's victim that leads to the output: "run away!"

This is a trivial example and does not surprise us. For, the main actor is a man, who is supposed to be endowed with consciousness and experience, which bring forth this sophisticated behaviour. However, Robert Rosen showed that this kind of behaviour is *not* exclusive to mankind, but that it is found at *all levels of biological organization*!

He demonstrates his assertion with the use of negatively phototropic organisms, where there is no question of learning or of consciousness. These organisms, as their name indicates, are attracted by darkness. This is, however, difficult to understand, because darkness itself has no physiological significance, that would be a stimulus for them to seek it out. Since they do so, darkness must be correlated with something positive for them. Rosen speculates that it might be the night moisture or the absence of sighted predators. Thus, these organisms change their present state in accordance with a prediction about the future, made on the basis of a model that associates darkness with some quality that favours survival.[90]

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[89] Here we use the web source "Anticipation info" at http://www.anticipation.info/navpages/nav_main.html.

[90] The difference between the first example of the "bear-man" interaction and the second one, lies in the fact that the latter is not a conscious decision of this organisms, but it is a in effect a "wired-in" model.

Another example one can find is in the story of the changing seasons that we drew at the beginning of the previous chapter. In autumn the trees lose their leaves, because they “know” that winter is coming and that they can survive the decrease in temperature only when they reduce the amount of water they consume. It is information carried by them, by each individual, from its very beginning, which rules their model of yearly behaviour.

Even more surprising is the fact that anticipatory behaviour can be found at the molecular level. There are many examples, particularly from biochemistry, concerning biosynthetic pathways, for instance, where an adaptive response to the increase of some of the components involved is shown.

Anticipation as a subject of study is very recent; Mihai Nadin calls it “a new paradigm” (Nadin: http.). Why was it overlooked for so long? Rosen thinks (Rosen 1972: http.) that the situation is even more serious. He says: “The failure to recognize and understand the nature of anticipatory behaviour has not simply been an oversight, but is the necessary consequence of the entire thrust of theoretical science since earliest times.” Again, the main reason is the principle of causality, together with the arrow of time. In most sciences it is still unacceptable to allow the present state of the system to depend upon future states. That is why any apparently anticipatory behaviour of any natural system *must* be interpreted as a reactive behaviour. Rosen calls it a *reactive paradigm*. But, if we want to reach accurate knowledge about nature we must develop an entirely new approach.

In accordance with this Nadin states (Nadin: http.): “For those who adopt the view according to which future states cannot affect a present state, anticipation makes no sense, regardless of whether one points to the subject in various religious schemes, in biology, or in the quantum realm. The situation is not unlike that of Euclidean geometry vs. non-Euclidean geometries. To see the world anew is not an easy task!”

“To see the world anew” is a challenge for both modern (post-modern) science and philosophy. In physics a “revolution in thinking” was initialised by the birth of quantum mechanics at the beginning of the previous century,[91] and since then a number of its conclusions have been applied to philosophical and other, more general, considerations. Among them one should mention Bohr's *principle of complementarity*, and Heisenberg's *relations of uncertainty* or quantum *non-locality*. All of these concepts (which we shall be discussed in more detail later in this chapter) have brought along completely new ways of thinking and interpreting the world, and they represent a new expectation for solving new kinds of problems, as in complexity studies for instance. Thus, many thinkers coming from different scientific disciplines have found inspiration in quantum mechanics. The two theorists mentioned earlier, namely Robert Rosen and Mihai Nadin are not any exception, as we shall see.

In philosophy, the modern stream begun somewhere between Hegel's dialectics and Kirkegaard's existential "qualitative dialectics", and have continued, via the modern and post-modern philosophy of the 20th century, up to now. The main new cognitive foundations that they declare are the acceptance of the *co-existence of contradictions*, considerable shift from the ontological level of description to the *epistemological level*, a release from strict bivalent logical rules, an acceptance of a *plurality of truths* and *discourses*, and laying stress on *language* and descriptive tools. These are all issues that we are going to meet within the following chapters.

Despite the fact that all this recent activity in both scientific and philosophical fields, that have no doubt considerably advanced our understanding of the universe and ourselves, one should nevertheless be aware of the danger of losing the right path to the finding truth, which should be the ultimate goal of all cognitive effort. The danger of misgivings is now greater than ever before, since most of these new concepts do not correspond with the sc. *common* sense that is always the first adviser we have.

There are two immediate ways in which to escape from this schism: to throw all these new ideas away and keep the "classical" approach, or to deny

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[91] We are aware of the fact that we neglect the importance of the Einstein's theory of relativity in this history of science.

the warnings of common sense and to be disposed to accept everything new without any critical evaluation. Both these positions are extreme ones and as always the best solution would be somewhere in the middle.

Another important aspect of complex systems closely connected with emergence, is adaptation. The word ‘adaptation’ comes from the Latin composite of *ad* what means ‘toward’ and *aptus*, which means ‘fitted’ or ‘appropriate’. One of the dictionary definitions says: *Adaptation = a form or structure, modified to fit a changed environment.* To decide whether or not a new emerging property (trait) is an adaptation is one of the main tasks of evolutionary biology.

All complex systems on earth that are alive, are adaptive systems, but there are many more systems that are either only parts or aggregations of living systems, or that are not even alive at all (Gell-Mann 2002). The first complex adaptive systems on our planet were the pre-biotic chemical reactions that lead to life, Gell-Mann continues. Biological evolution itself is a complex adaptive system, and so is the behaviour of each individual organism resulting from biological evolution. However, not only whole organisms but also their parts can function as complex adaptive systems, the human immune system or the human brain, for example.

When we take a step to the higher level, we observe that the behaviour of organized groups of people represent complex adaptive systems as well; the whole of human cultural evolution, or human organizations such as business firms, for instance. According to Gell-Mann there are also non-living adaptive systems. Recently computer software was developed that shows many of the attributes of complex adaptive systems (cf. Coveney 1995).

On the other hand, one should not automatically assume that every feature of an organism is an adaptation, i.e., that it was moulded for its current function by natural selection. In his paper called “The spandrels of San Marco and the Panglossian paradigm: A critique of the adaptationist programme” (Gould 1979) Stephen Gould and Richard Lewontin introduce the word ‘spandrel’ to name features that arise without initial adaptive functions (e.g.

those that are architectural by-products of development) but take on new functions later in evolution.[92]

> We talk about the "march from monad to man" (old style language again) as though evolution followed continuous pathways to progress along unbroken lineages. Nothing could be further from reality. I do not deny that, through time, the most "advanced" organisms has tended to increase in complexity. But the sequence [allocated in most texts] from jellyfish to trilobite to nautiloid to armoured fish to dinosaur to monkey to human is no lineage at all, but a chronological set of termini on unrelated evolutionary trunks. Moreover life shows no trend to complexity in the usual sense – only an asymmetrical expansion of diversity around a starting point constrained to be simple.[93]

2. Complexity between chaos and order

> *The absolute sound-chaos, e.g. the tuning of the orchestra, although it contains boundless the potential of music, one cannot listen to it – it is noise. Only when order enters into the chaos is comprehensible sequences, forms, cords and the construction of the composition provided. The delight that we experience in music is on the edge between order and chaos, where we are still taken by surprise, but we are still able to understand; the place of oscillation between accepting the centre of chaos (were everything is possible) and demanding the centre of order (which is necessary). It is not in vain that the music of Bach is considered to be the height of creativity – i.e. unbelievable order within the chaos. On the other hand, the constantly round stereotyped playing machine does not satisfy us. The predictable order is dead* (Chvála, 2002).[94]

If we look at the world that surrounds us we can see a huge number of structures, but very frequently we can also find chaos.[95] We can mention our example from the first chapter concerning climate as an example. We saw that, despite the fact that it is a very complex thing, seasons change according to a predictable pattern. Nigel Goldenfeld and Leo P. Kadanoff say in their paper published in *Science* in 1999 (Goldenfeld 1999):

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[92] Here we use the public lecture on adaptation by Chris Andrew of The University of Chicago.

[93] Gould, S. J. (1993) Tires to Sandals, *Eight Little Piggies: Reflection in Natural History*, W. W. Norton & Company, New York, p. 322.

[94] Translated by A. Cejnarova.

[95] Chaos is the sensitive dependence of a final result upon the initial conditions that bring it about (Goldenfeld, 1999).

> A complex world is interesting because it is highly structured. A chaotic world is interesting because we do not know what is coming next. … Our world is both complex and chaotic».

Many people that are interested in the emergence of complexity have already recognized the presumption that nothing new can emerge from systems with high degrees of order and stability, such as crystals, and that completely chaotic system are too formless. Truly complex things appear at the border between rigid order and randomness as J. Horgan states in (Horgan 1995). That is why one of the most frequent definitions of complexity is based on the notion of “the edge of chaos”.[96]

In accordance with these suggestions Tamas Vicsek (Vicsek 2002) proposes the example of turbulent flows and the brain. These are clearly very different systems, but they share a few remarkable features. It is an impossibility to predict their behaviour as a whole by merely extrapolating from the behaviour of their units. He continues:

> Who can tell, from studying a tiny drop or a single neuron, what laws describe the intricate flow patterns in turbulence or the patterns of electrical activity produced by the brain? …Such systems exist on the edge of chaos – they may exhibit almost regular behaviour, but can also change dramatically and stochastically in time/or space as a result of small changes in conditions.

Thus, such behaviour seems to be a *general property* of all systems that are complicated enough (complex).

All isolated systems[97] have a natural tendency to develop into a state of thermodynamic equilibrium.[98] The indicator of this development is a quantity called entropy. Entropy was defined in the 19th century by Clausius, who studied irreversible systems, where changes only happen in one direction, but in spite of this, energy must conserved – as the first law of thermodynamics demands. Entropy was introduced to represent the inner state of such systems in each moment. The most interesting feature of

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[96] For instance Christopher G. Langton of the Santa Fe Institute suggests that the complexity of a system may be equivalent to its capacity for computation. And he found that this capacity maximum lies in the region between highly ordered states and chaotic ones, which he proved with the use of cellular automaton (according to Horgan 1995).

[97] I.e., systems that do not exchange energy with their environment.

[98] This is a state where all changes of temperature, volume or pressure are kept in equilibrium.

entropy is the fact that the entropy of an isolated system can only stay constant or increase. However, the greatest isolated system is the whole Universe itself. Therefore in 1865 Clausius wrote (Clausius 1865: 353; cf. Prigogine 1984):

> *"Die Energie der Welt ist konstant.*
> *Die Entropie der Welt strebt einem Maximum zu."*[99]

And this is a famous formulation of the two basic laws of thermodynamics.

Entropy is sometimes identified with the measure of disorder within the system. According to this law, all isolated systems tend to the state of maximal disorder, but our experience shows that reality is different. All natural systems, on the contrary, show a tendency to some order, which is, as was said at the beginning of this chapter a presupposition of creating complexity. The reason is that complex systems are always *open* systems as we stated in Chapter II.[100]

Isolated systems not occur very frequently in nature, if they even exist; they are mostly only a simplification. Except for the universe as a whole, most of the systems that exist within it are open systems, i.e., they exchange energy, mass and information with their surroundings. So, most systems do not find themselves in stationary states, but fluctuate and vibrate. Sometimes these fluctuations are so strong that they even interrupt the already existing order; I. Prigogine calls this crucial moment "singularity" or "bifurcation" (Prigogine 1984).[101] At this point it is possible that the system will decompose into chaos, or "jump" to a higher level of order or organization, what Prigogine calls "dissipative structures".[102] Unfortunately, nobody can say in advance which of these two scenarios will be realized, and in this sense these changes are unpredictable. The most important impact of Prigogine's theory is based in

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[99] "The word energy is constant. The word entropy efforts for reaching a maximum." – transalted by the author.

[100] The view that, simultaneously with the increase of disorder within a system, the system is enriched by information, is quite popular. An often-quoted illustration uses text written on a sheet of paper as an example. A perfectly ordered sequence of a small number of letters carries no or very little meaning. Conversely, at first glance the disordered overflows from letters on a white paper can represent a rich knowledge-text, e.g. a philosophical sentence, or a poem. However, a text is composed of words and sentences and this means *structures*. So, it supports the conviction that in a place where one would suppose only broad meaningless chaos resides, complexity is in fact born.

[101] Bifurcation – the branching of solutions.

[102] They are called "dissipative" because, in comparison with the simpler structures they replace, they need more energy to be kept in this higher state.

his deep conviction that order and regularity can really come to exist out of chaos, spontaneously and through self-organization.

The physics of chaos or non-linear dynamics have recently significantly penetrated into ecology, for instance. For many decades it was believed that the animal population would naturally hover at equilibrium. If not, this situation was explained by means of the unaccountable effects of weather, disease, and other sources of so-called environmental noise (Zimmer 1999: 84). That assumption was however shaken by the work of Sir Robert May in the 1970s. He started to explore simple ecological models describing how populations of damselfish changed generation after generation. According to a typical model this population should increase up to a state of equilibrium, and above that level it should decline again.

Damselfish were also studied by Maria Milicich. She observed a number of their larvae leaving the mother-reef (the Great Barrier Reef), and a number of larvae that, 19 days later, returned as mature larvae. Her goal was to figure out what determined how many larvae reached maturity.

One would naturally expect that she found a regular quantity of new adults every month. But the opposite was true. She observed huge fluctuations that were difficult to explain. She tried almost everything – from rainfall to the brightness of the moon, hundreds of variables, but everything was in vain.

She reached an epiphany when she came across the idea to apply non-linear mathematics to her results, describing the abundance of phytoplankton off the coast of California. Nine years later she published a report in *Science* (Milicich 1999: 1528) where she and her co-authors showed that it was possible to successfully model the dynamics of a damselfish population with only three factors – the moon's phase, turbulence around the reef, and wind blowing over the water – using non-linear equations. "From hundreds and hundreds of potential correlates, all of sudden three dropped out, and they made perfect ecological sense," says Milicich – according to (Zimmer 1999: 84).

The same results were reached by May. Also in his model the population of a preceding generation was not directly proportional to the current one. It might be more; it might be less; it might even be the same.

What this means is that it was non-linear. What is important, in spite of the fact that Mays's model was apparently simplified, it could – thanks to its non-linearity – produce complex patterns as can be directly observed in nature. These were random-looking patterns produced by non-random equations.

The chaos contained in these models was so significant that ecologists began searching for it in the real world, because it promised to overturn the old ideas about the balance of nature. "Whatever the final verdict on chaos in nature may turn out to be", Zimmer says, "the success of non-linear dynamics won't stand or fall on it." The process of searching for the forces that drive such spectacular population dynamics won't be stopped.

But this is far from being all. Now ecologists are learning that there is also noise in the environment. Up to recently most ecological models have only looked at a particular species etc. They have not taken into consideration the effects of random variability coming into the model from the outside. However, it is necessary to also bring noise into non-linear models.

As one can see from the practical applications of achievements in physics to different fields of interest, i.e. ecology in this particular case, the theory of chaos works quite well. It is definitely a very promising scientific approach, closely connected to complexity studies, which will surely still surprise us by new insights into the nature's secrets. However, one should keep in mind that all natural creatures and systems in general are so unique that they will always resist any strict mathematicisation as an unavoidable fact. The only thing that we can reach seems to be to get closer to the "kitchen" of the universe and to lift some of the pot-covers. However, what exactly is inside the pots and what the recipe is, is still hidden to our eyes.

To conclude this section we can quote a definition as it was proposed in (Poon 1995):

> Complex systems are systems with complicated and intricate features, having both elements of order and elements of randomness.

The dynamics of complex systems, therefore, tend to alternate among different behaviours (ranging between order and randomness). However, in each moment we always observe only one particular bit of behaviour. Why this is so and what mechanisms are responsible for “choosing” the proper one has been the subject of research recently.[103]

3. Organizing principles

To grasp the possible mechanisms of the originating of complexity represents a boom in all contemporary complexity sciences. One of the most often quoted terms in this connection is a ‘self-organized critical phenomenon’. According to this theory when a system reaches the sc. critical state, events, which would otherwise be uncoupled, become correlated, and thereby complexity originates (Bak 1995).

Per Bak, who is considered to be a founder of the science of *self-organized critical systems* starts his paper with polemic with Steven Jay Gould who in his book *Wonderful Life* (Gould 1989) states:

> Many large domains of nature – cosmology, geology, and evolution among them - must be studied with the tools of history. The appropriate methods focus on narrative, not experiment as usually conceived».

Per Bak, on his part, however, disagrees with Gould’s view that the traditional scientific method is not appropriate to study complex phenomena and defends the traditional scientific method.[104] He proposes using of the theory of self-organizing criticality (SOC) that is empirically well observable.

The basic idea of SOC is as follows: The large dynamical systems naturally evolve, or self-organize, into a highly interactive, critical state where a minor perturbation may lead to events, called avalanches, of all sizes (Bak 1995). When a single grain of sand is dropped on a pile, it usually causes a few grains to fall, but every so often it will initiate a large avalanche. This theory has also been supported by number of experiments (cf. Held 1990).

A research group from IBM Thomas J. Watson Research Centre led by Glenn A. Held has succeeded in simulating the growth of a sand-pile by

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[103] Cf. (Poon 1995); in this article it is for example proposed that what we observe at a given time is often sensitive to minor perturbations, which are, in some simple cases, possible to study and to model. Moreover, if succeeded it allows control a complex system’s behavior to some extent.

[104] The following argument will be recalled again later when we deal with the descriptive problems of complexity.

allowing grains to fall on the pile continuously for a few hours. They then watched avalanches of sand cascade down the pile. When a stabilised balance occurred, it was controlled by a computer. The results they obtained after two weeks strongly supported the theory that the sand-pile had indeed organized itself to a critical state (Held 1990).

The theory of SOC has been then successful not only in explaining the mechanisms of avalanches, but also those of earthquakes and in describing the distribution of their epicentres[105] or in the modelling of traffic[106]. All of these models have something in common: the number of elements involved is always conserved. For instance, the number of grains of sand in the pile always equals the number that was dropped on the pile minus the number that fell off. The conservation of elements is an important feature of many systems that naturally evolve to a critical state (Bak 1991: 30).

In 1970 the mathematician John H. Conway invented a game called “the game of life” - cf. (Coveney 1995). The aim of this game is to simulate the evolution of a colony of living organisms and thereby to imitate the origination of complexity in nature. At the beginning of the game the elements (standing for organisms) are randomly placed on a board composed of square sites. Each site is occupied by one organism at most and is surrounded by eight neighbouring sites. The number of organisms that occupy the eight neighbouring sites gives the status of each site at each turn. Two live sites around an empty or occupied site means: no change for this site. Three live sites around a site cause that this site will give birth to a new organism or the old organism – if present – will stay alive. More or less live sites surrounding a particular site will bring forth the death of the organism, due to overcrowding or loneliness. The game continues until the system reaches a stable state containing stable colonies.

A new experiment realized twenty years later (Bak 1991: 33) tried to compare this game with a model of sand-pile avalanches. Once the system settled into its rest-state the researchers added a single organism at a random

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[105] According to this law the longer you have waited since a large earthquake at a given location, the longer you can expect to still have to wait… Earthquakes are clustered in time, not periodic (Bak 1997).

[106] One can even reconise the clustering effect with buses – “nothing for ages, then three come along at once!” (ibid.).

position, waited until the system settled again and then repeated the procedure. Then the total number of births and deaths after each additional perturbation was measured. They found that this system also organized itself to a critical state.[107]

A conclusion of this article of fundamental importance is the speculation that these models may have important ramifications in real biology. The game of life can thus be seen as a toy model of co-evolutionary systems. The co-evolutionary process takes the system from an initial random state to a highly organized, critical state, with complex static and dynamic configurations. It appears that the complexity of global dynamics is intimately related to the criticality of dynamics. In fact, *the theory of complexity and the theory of criticality may generically be one and the same thing!*

So, empirical observations indicate that biology operates at a critical state (Bak 1995: 6693). In biological evolution there are long periods of relatively little activity, interrupted by narrow intervals of large activity. This conclusion is also supported by findings in palaeontology: the distribution of lifetimes of fossil genera appears to obey the same law – (cf. Raup 1986: 1528).

We have just finished a small journey into the world of "hard science" trying to describe empirically the process of constituting the complexity of a given system. The two crucial attainments we should notice are mainly that the theory of SOC could be an answer to the question of *how* complexity originates, and secondly, that these matters *are* analytically and empirically graspable.

Understanding that self-organization is a significant force in evolution is among the most progressive views, because ever since Darwin it has been believed that the only source of order (i.e. complexity) in living systems is natural selection. Up to now science has repeatedly proven that, on the basis of mathematical models for biological systems that exhibit self-organization, one can make predictions that are consistent with the observed properties of organisms (Kauffman 1991: 78). According to Kauffman, Darwinian theory

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[107] Of course, this experiment had many variations, for example the space conditions were varied, organisms were added not randomly but according to some patterns etc. We do not intend to discuss these variations in detail.

alone cannot account for the origin and consecutive evolution of life – we must begin to understand it as an alliance between selection and self-organization.

The idea now is as follows: when a system of simple chemicals reaches a certain level of complexity or interconnectedness[108] it undergoes a dramatic transition or phase change. For example molecules spontaneously begin combining to create larger molecules of increasing complexity and catalytic capability, i.e. autocatalysis. Then the further evolution to some extent continues to obey the Darwinian selection rules. Although the behaviour of complex systems seems chaotic – as we saw earlier in this chapter – this is only one part of its behaviour. There is also a counterintuitive phenomenon, i.e. an ordering principle that Kauffman calls *anti-chaos*, which is responsible for the observed fact that complex systems do not evolve randomly but tend to converge toward a relatively small number of patterns, or attractors[109].

Max Planck stressed that there are two kinds of changes in nature "It appears," he wrote, "that nature "favours" some particular states" (Planck 1925: 353). The irreversible increase of entropy describes the system approaching a state that "attracts" it (cf. attractor), which benefits the system and from which the system cannot escape, due to its own "will". According to Planck, nature does not allow such processes – it finds those final states less "attractive" when compared with the initial states. Reversible processes are limit-cases where nature has the same inclination toward both initial and final states and therefore it is possible to realize a transition between them in both directions. This is a position of thermodynamics.

In dynamics, on the other hand, a system changes in accordance to its trajectory, which is fixed forever and its initial state is never forgotten (since the trajectory is forever determined by the initial conditions). However, in an isolated system all non-equilibrium states cause changes toward the same kind of an equilibrium state. At the moment when the system reaches the

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[108] This is related to both the edge of chaos concept and Bak's theory of self-organized criticality.

[109] To define an attractor is not simple. For instance, A. Tsonis (Tsonis 1992: 67) defines it as "a limit set that collects trajectories". In other words it is "a set of points such that all trajectories nearby converge to it". The existence of attractors is usually connected with the long-term behavior of a system (which evolution definitely is).

state of equilibrium it "forgets" its initial conditions, i.e., the way of its development - cf. (Prigogine 1984).

So, now we have to do with two completely different kinds of description: dynamical – used for the world of movement and thermodynamics – the science of intricate systems, based on the notion of entropy. This is a kind of dichotomy that represents a problem that has been discussed since the formulation of the laws of thermodynamics.

4. Quantum mechanics – the source of complexity?

Murray Gell-Mann says in his famous book, *The Quark and the Jaguar* (Gell-Mann 1994, cf. Horgan 1995: 79):

> The probabilistic nature of quantum mechanics allows the universe to unfold in an infinite number of ways, some of which generate conditions conducive to the appearance of complex phenomena. As for the second law of thermodynamics, it permits the temporary growth of order in relatively isolated, energy-driven systems, such as the earth».

It means, when understood literally, that we do not actually need any new science or tools to explain the emergence of order and complexity in nature. Everything can be understood and explained on the basis of quantum-mechanical laws.[110]

Although such a view is rather reductionistic it is still proliferates among contemporary scientists. The reason is that quantum mechanics has provided a number of powerful laws allowing a variety of interpretations that give the impression that one can explain almost anything with their help. We shall try to sketch some of the fundamental attainments of quantum mechanics in this section.

If we want to understand the new ideas brought to life by quantum mechanics, we must start with some historical facts to get the context necessary for getting into the problem.

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[110] The resulting reduction in concepts can, however, also be considered useful: it represents an alternative to repeating the "complete experiment" with all degrees of freedom.

By about 1925 it was already clear that the existing spectrum of attitudes towards the physics of the microworld was already so wide that the formulation of a unified and coherent theory was already almost impossible. On the contrary, one would rather have supposed that quantum mechanics would develop into different, mutually independent streams, considerably influenced by personal attitudes of their authors (Müllerova 1999: 30). And this actually happened to some extent.[111] It is beyond the capacity of this work to mention all the important names and their concepts and we shall limit ourselves to only the few of them that are important for the issue at hand.

Among the most pronounced personalities of the history of quantum mechanics are no doubt Werner Heisenberg[112] and Niels Bohr.[113] Heisenberg can be counted as a founder of the corpuscular concept of the microworld. According to him, the world is composed of different bounded particles. However, these particles are not ”real” in the ordinary sense of the word. They rather create a world of *potentialities* or *tendencies* other than things or the reality.

Niels Bohr, on the other hand, coined the idea of *wave-particle dualism*, i.e. that it is useful and necessary to apply both the language of wave mechanics [114] and a particle concept to atomic theory, according to a particular situation. However, both of these languages are subject to some constraints, and thus the main task of the new physical theory becomes to formulate these restrictions and to determine conditions, which demand the particle-based description or the wave one. Bohr believed that the answer one should look for lay in direct analyses of particular simplified physical situations. Heisenberg, however, was opposed to this opinion and claimed that the only answer is hidden in the formal structure of the theory and therefore one should concentrate on it.

These disputes culminated in February 1927 when Bohr left his institute in Copenhagen for a short holiday, and thereby cleared a space for

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[111] Let us compare, for instance, the wave mechanics of E. Schrödinger and the sc. matrix mechanics of W. Heisenberg.

[112] W. Heisenberg (1901-1976).

[113] N. Bohr (1885-1962).

[114] Sc. wave mechanics was formulated by E. Schrödinger as an alternative concept of the microworld to Heisenberg’s corpuscular model, based on the notion of the wave function Ψ that represents all micro-particles and carries all information about them.

Heisenberg, who took advantage from and worked hard on his own ideas. The main question he was occupied with was how it is possible to describe the trajectory of an electron in a cloud chamber (Heisenberg 1979). One could observe this trajectory; however, theory did not allow one to describe it.

Since Heisenberg unreservedly believed in then a mathematical formalism, he tried rather to cast doubt on the existence of the trajectory of the electron. He thought that what one observed in a cloud chamber is only a discrete succession of uncertain positions of the electron. So he put the question as to whether it is possible to describe a situation within quantum mechanics where an electron finds itself in a place, with a given uncertainty, and at the same time its momentum has been changed by uncertainty too? A short calculation proved that this was the case. The obtained relation was called a *relation of uncertainty* and has since then enjoyed great popularity.[115]

The main reason why the originally purely technical instrumental formulation for this particular situation – uncertainty relations – has become so famous consists in the fact that was immediately interpreted as a general principle, and applied to a variety of other situations; also by Heisenberg himself. Uncertainty is now seen by the majority of physicists as a fundamental reality of the microworld (and not only microworld but implicitly of the whole world, having the ‘micro’ part as its substrate).

The most common interpretations are the following: either it means that we cannot observe or precisely measure two properties of a given micro-system simultaneously – because the one observing causes uncertainty in the observed (weak form); or, all statements considering the microworld are uncertain (the stronger form); or even, all knowledge about the world is uncertain (the strongest form). Heisenberg, for his part, apparently was inclined to the second version. Moreover, according to him, one can only speak about the ‘reality’ of a system when one measures or observes it; in the meantime, all judgements are meaningless. In his famous book *Physic and Philosophy* Heisenberg says (Heisenberg 1959: 144):

> …If, therefore, the atomic physicist is asked to give a description of what really happens in his experiments, the word ‘description’ and ‘really’ and ‘happens’ can only

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[115] The mathematical formula is as follows: $\Delta p \, \Delta x \geq \hbar/2$, where p is momentum of an electron, x is its position and ħ is the sc. reduced Planck constant.

> refer to the concepts of daily life or of classical physics. As soon as the physicist gave up this basis he would lose the means of unambiguous communication and could not continue in his science. Therefore, any statement about what has “actually happened” is a statement in terms of the classical concepts and – because of thermodynamics and uncertainty relations – by its very nature incomplete with respect to the details of the atomic events involved. The demand to “describe what happens” in the quantum-theoretical process between two successive observations is a contradiction *in adjecto*, since the word ‘describe’ refers to the use of the classical concepts, while these concepts cannot be applied in the space between the observations; they can only be applied at the points of observations.

As a consequence, the world started to be regarded as a collection of unshaped entities that are formed by our observations[116] and the independent reality of the common sense did not exist any more.[117] Man plays an active role in the formation of the world. Not only through his acts, but also through the language he uses. Heisenberg continues in this vein in following paragraph (Heisenberg 1959: 180):

> In fact I believe that the language actually used by physicists when they speak about atomic events produces in their minds similar notions as the concept ‘potentia.’ So the physicists have gradually become accustomed to considering the electronic orbits, etc., not as reality but rather as a kind of ‘potentia.’ The language has already adjusted itself, at least to some extent, to this true situation. But this is not a precise language in which one could use the normal logical patterns; it is a language that produces pictures in our mind, but together with them the notion that the pictures have only a vague connection with reality, that they represent only a tendency toward reality.

Another concept is closely related with Heisenberg’s uncertainty relations: the *principle of complementarity*, formulated by Niels Bohr. One of the most famous mysteries of quantum mechanics is the fact that quantum particles behave as true particles sometimes and as waves at other times. It seems that what behaviour we observe depends on the kind of experiment we choose. For example, in a cloud chamber we can directly observe the impact of individual particles. On the other hand, when we let particles fall on the optical diffractive grid, we observe the emergence of dark and light spaces on

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[116] Here the influence of our observation stands for the interaction with environment.

[117] This is an attitude that goes strongly against the grain of the classical concept, which stresses the ontology of things.

the screen – which points toward the wave character of these species. To understand the logical nature of this sc. wave-particle dualism was the main task that then occupied the minds of physicists.

Niels Bohr, for his part, was convinced that wave and particle pictures represented two complementary but simultaneously mutually exclusive ways of describing physical reality. Their use depends on the particular experimental situation. This conclusion annoyed Bohr – and some other, more “realistically” oriented people – thanks to his strong inclination toward existential philosophy, by which he had been influenced since youth through his father; Kierkegaard’s “qualitative dialectics” in particular.[118]

Nevertheless, not only Bohr sympathised with dialectics; W. Heisenberg said about principle of complementarity (Heisenberg 1979):

> … the third possibility that has arrived with quantum-theoretical complementarity could be fruitful and leads to the space of the real world. … The synthesis of antithesis can be fruitful only when something *quantitatively new* emerges.[119]

N. Bohr added (ibid.):

> One who has really understood quantum theory would no longer speak about dualism. He would understand the theory as a unified description of atomic events that, only when converted the innate language, can look really ambiguous.

Therefore, the only possible way to speak about microparticles themselves is by using the mathematical scheme as the only possible replacement of the innate language, or combining it with a language-based on non-bivalent logic.

This is the traditional conclusion of the sc. Copenhagen interpretation of quantum mechanics,[120] and is accepted as a strange but true fact about the microworld. However, if it is also true that all phenomena in the universe can

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[118] Kierkegaard’s dialectics differs from Hegel’s dialectics mainly in the proposed “solution” of dialectical situation. While Hegel sees an outlet in the synthesis of the already existing antithesis (cf. his famous triad thesis – antithesis – synthesis) Kierkegaard says that co contradiction is solvable at all. Individual alternatives are once and for always mutually exclusive.

[119] Heisenberg probably had in mind the possibility that the principle of complementarity could uncover a drapery hiding the “real world”, i.e. the third possibility, that stays hidden and only occasionally “appears” in different, often even in contradictory, features. This thought was recently elaborated on by B. d’Espagnat in the theory of the sc. veiled reality (cf. Müllerova 1999).

[120] It was named after its place of origin, i.e., Copenhagen in Denmark.

be derived from quantum mechanics, then we should apparently re-evaluate our ‘classical’ view of the world, and perhaps we should concede that “more things are possible than we have ever thought”. For instance, apparently contradictory features can co-exist within one system. Or, we can to some extent adapt reality to our requirements, ensuing from the method of observation. So, now it is clear where the opinion of Murray Gell-Mann - that everything can be explained on the basis of quantum mechanics - comes from.

However, there is a significant danger inherent to such an approach, and even two at once: firstly, to attribute everything that we cannot explain to quantum mechanics is the easiest solution, but not necessarily the right one. By this act we either only postpone the problem to another level, which is at least as mysterious to us, or we misinterpret the problem and look for the solution in the wrong places.[121] Secondly, there is still the possibility that not all of the statements of quantum mechanics are right and that, by blindly believing its conclusions, one can disseminate further false concepts. So, one should by all means by very careful when trying to apply quantum mechanics to macroscopic things.[122]

When speaking about quantum-mechanical “novelties” one should not leave another concept which significantly opened the door to many vague interpretations of a number of events out of consideration, namely the *probabilistic concept* of quantum mechanics.

Max Born proposed this new interpretation of quantum mechanics – strictly speaking of the wave function Ψ – and he was awarded a Nobel Prize for it in 1954 (Born 1955). It is not our task to give an overview of the whole theory, so we restrict ourselves only to mentioning the most important conclusion that result from it.

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[121] Unlike Gell-Mann we are not convinced that everything arises from the laws of quantum mechanics but on the contrary, we believe that some new phenomena emerge on a higher level as products of complexity and they are not in any way reducible to quantum phenomena.

[122] Of course, there are many rigorous mathematical approaches trying to conciliate these two worlds, i.e. micro- and macro-, for instance theories solving sc. “classical limit of quantum mechanics”, but this is not what we have in mind in here. We mean rather the transferring of the verbally unsure interpretations of quantum events to the non-quantum region, and particularly all generalization formulated on the basis of quantum-mechanical theories and results.

According to Born, quantum mechanics does not respond to the question of what the final state of a given system is, but rather to what the *possibilities* of its final state are. In Born's interpretation, the square absolute value of the wave function determines the probability density of finding a particle in a particular place at the particular instant.[123] The total probability of finding a particle somewhere in space, before as well as after a collision (i.e. detection) is equal to *one*. In an article (Born 1926: 803) Born sums up this situation in a frequently quoted sentence: "The particle movement is directed by the laws of probability, but probability itself is spread according to laws of causality".

The notion of probability in Born's theory is completely different than the classical one used in statistical mechanics, for example. In contrast to the latter the former one does not purely add probabilities, but works also with sc. "interference terms", forming a new kind of a wave field[124]. However, a probability wave in Born's formalism is not a three-dimensional wave, like radio waves for example, but a wave in the many-dimensional configuration space, and therefore a rather abstract mathematical quantity.

Born's waves are often understood in the sense that they are observable only as probabilities of the finding of particles in a given place.[125] W. Heisenberg (Heisenberg 1959: 45) characterized them as:

> …a mixture of two things, partly a fact and partly our knowledge of a fact. It represents a fact in so far as it assigns at the initial time the probability unity (i.e., complete certainty) to the initial situation: the electron moving with the observed velocity at the observed position; "observed" means observed within the accuracy of the experiment. It represents our knowledge in so far as another observer could perhaps know the position of the electron more accurately. The error in the experiment does – at least to some extent – not represent a property of the electron but a deficiency in our knowledge of electron. Also, this deficiency of knowledge is expressed in the probability function.

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[123] $P(\mathbf{x}, t) = |\Psi(\mathbf{x},t)|^2$.

[124] In other words, a new space for the "existence" of exotic possibilities. One can continue in this direction until one reaches the famous quantum paradoxes, the *paradox of Schrödinger's c t*, for example. Regardless of what are these paradoxes show exactly, they have something in common, they deal with a different "kind of reality" where, for instance, a cat can be simultaneously dead and alive until the moment someone opens the box and has a look inside.

[125] I.e., only through the measurement of $|\Psi|^2$.

Born himself said about “his” waves following (Born 1964):

> The question whether the waves are something “real” or only functions for description and prediction of a phenomenon is only a matter of a choice. I, personally, like the idea of the probability wave, even in the 3-dimensional space, as a real thing certainly more than to see it only as a tool for mathematical calculations… Quite generally, how can we rely on probabilistic predictions when we do not relate it to something real and objective?

Although Born’s interpretation of the wave function sounds quite “realistic” it still leaves room for ambiguity in the description of systems. Moreover, if one identifies the probabilistic features of the theory with the nature of things themselves, it dramatically changes our understanding of their “ontology”[126] and, implicitly, of the whole reality. So, this theory does not provide us with a satisfactory and exhaustive description of any system we would demand to use it for, nor does it explain the origins of complexity in general.

3. The middle way

“The middle way” is a theory proposing the possibility that as-yet-undiscovered organizing principle might be at work at the mesoscopic scale – intermediate between atomic and macroscopic dimensions – that is responsible for the emergent, organized behaviour of some systems (e.g., crystallinity) and recently formulated by a group of researchers from different American labs, led by David Pines (Laughlin 2000: 32).

Contemporary science is already able to predict the behaviour of atoms or small molecules with reasonable accuracy, thanks to the effective laws of quantum mechanics. However, problems occur when one wants to determine the behaviour of larger things, because the computer requirements would be so huge that the resulting errors of counting would immediately run out of control. But, very large aggregations of particles have some astonishing properties at the same time, such as the ability to levitate magnets when they

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[126] S. Goldstein speaks in this context about sc. primitive ontology, i.e. what these things are (Goldstein 1998: 38). And this is quite a “revolutionary” matter, because, according to standard interpretations of quantum mechanics, one cannot raise questions of the ontology of things for “they have no sense”. This kind of question is simply forbidden.

are cooled to cryogenic temperatures (ibid.). “How can this be?” – the authors ask – “The answer is that these properties are actually caused by collective organizing principles that formally grow out of the microscopic rules but are in a real sense independent of them.”

It is true that in respect of size physics is divided into two domains: microphysics and physics of the “big things”. The scale gap between them is, however, enormous. Imagine the distances between atoms and small molecules on one the hand, and the size of a macroscopic matter on the other hand! There is a large regime lying in between, which we cannot see and which we know very little about.[127] “It is a desert” – the authors say – “But, as we all know, there is life in the desert.”

What the authors try to show is that it is very well possible that, at the mesoscopic scale, self-organization can take place, just as it does at the macroscopic level – which can be considered as already proved. This would have profound implications for all sciences. However, we have not had any clear proof for that up to now.

As an example of interesting mesoscopic behaviour one can take the functioning of large molecules in the life-processes. For instance, proteins can catalyse in a vast number of unrelated chemical reactions. They can pick out one substrate from thousands of chemically similar ones. They can act as computers – the authors continue – and can alter their activity through the presence of specific attractor molecules in their environment etc. One can also find similar interesting behaviour in non-biological systems. . According to the authors, gasses, for example, which have structure on this scale, exhibit a strange low temperature-specific heat, and at higher temperatures, memory effect, and non-ergodicity, i.e. behaviour one can also find in protein crystals. They are unstable, and age, and the like.

Unfortunately, due to experimental difficulties in a range of mesoscopic phenomena this scientific branch is still in its infancy. Of course, we have some techniques to look at such objects, scanning tunnelling microscopy, for example, or atomic force microscopy, but the problem is that with these methods we can only stay on the surface of complex objects. Other

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[127] It is too small for direct observation, but too big to be counted correctly.

techniques that would provide a three-dimensional picture – such as time-dependent X ray spectroscopy for example – are still under the development.

But, if the existence of organizing principles at the mesoscale is proved, “the framework for their understanding will be an extraordinary help in the effort to create an entirely artificial system with the complex adaptive behaviour characteristic of life” – the authors conclude their article (Laughlin 2000: 37).

> Such artificial systems should be capable of a variety of functions that present biological systems cannot perform… Organization following similar principles may well be manifested in astrophysics. Complex structures already have been proposed for the exotic matter expected in neuron stars, while ideas developed to explain mesoscopic organization on Earth may be useful in explaining the origin of large-scale structure in the universe».

In this section we raised the question of where complexity originates and what the mechanisms of creating complexity are. How can we capture and describe the moment when living organisms start to develop from a soup of chemical molecules?

We called the initial state where chemical molecules find themselves in unordered motion, not obeying any rules, *chaos*. Such a state is unpredictable and bearing “zero” information.[128] Then, due to the influence of some outer or inner cause, the system starts to change. Whatever happens, the resulting process leads to more organized structures and to a state of more advanced relations between these structures. The phenomenon where something new originates (or is observed although it has always existed) we called *emergence*.

The state opposite to chaos we described by the expression: *absolute order*. We showed that the only region that is interesting from the point of view of complexity is the one just between these two extreme positions – i.e.

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[128] Actually, this is not exactly accurate, since the system composed from molecules already represents a kind of developed and ordered system, for molecules are ordered structures by themselves. For our purposes, however, when we want to continue in our considerations up to the most organized structure in the universe, i.e. man, we can allow such simplification and inaccuracy. Another argument against this statement can be formulated as follows: if such a system carries no information at all then it cannot develop into any more sophisticated forms, since it does not “know” that it should do it. Then the only possibility rests on the working influence of some outer Cause, e.g. God – Creator.

between chaos and order. We called it – and exaggerated – “the edge of chaos”. This is the area where complexity exists. Now we have nothing to do with the unorganised soup of chemical molecules anymore, but with already organized structures, further developing towards living beings.

But, how do these structures “know” in what direction they should develop and what the resulting forms should be? According to Robert Rosen it is the phenomenon called *anticipation* that is responsible for leading the process of evolution. He proposes the idea that ‘emergence’ and ‘anticipation’ are two inherent aspects of complexity and that all complex systems are concurrently anticipatory systems. In other words, they are determined in the sense that they “know” what the terminate state is that they should reach. In this manner our first and simplest creatures are not left with uncertainty about their future, but will fulfil their own inherited plans.

It sounds like a good explanation, however, for many thinkers it is still not completely satisfactory. Most of us are keen on knowing what *the organizing principles* that rule the origin of complexity are. Actually, to grasp these mechanisms contemporary represents the main stream in contemporary complexity research. Up to now many theories and hypothesis have been proposed; among them *the theory of self-organizing criticality* (SOC), first formulated by Per Bak, stands out. According to this theory all large dynamical systems naturally evolve into a sc. critical state where a small perturbation may cause avalanches of all sizes. SOC, first formulated for purely physical systems, was also successfully applied to real biological systems. It appeared that biologic systems also develop naturally from an initial random state to a critical state with complex static and dynamic characteristics. The idea is as follows: when a system reaches a certain level of complexity it undergoes a kind of phase-change and “jumps” into a significantly more complex state, continuing until the terminate state. It is believed – by advocates of SOC theory – that, when combining it with the Darwinian theory of natural selection, it can explain all evolutionary processes of biological systems on Earth.

A slightly different approach to the problem of the origin of complexity comes from physics itself and it proposes the idea that the source of complexity can be found in quantum mechanics. Support for this attitude was found in some partial successes of quantum-mechanical theory that led some people to the conviction that “everything can be explained on the basis of quantum mechanics”. However, this idea can be considered as final, mainly because quantum mechanics only answers some special questions, and not really those that we are interested in.

The last section we devoted to the theory proposing another solution for the organizing principles problem. It says that at the mesoscopic scale – between the atomic and macroscopic dimensions – an as yet-undiscovered organizing principle may be at work that is responsible for emergent organized behaviour. Although, this idea is still rather a hint in some direction than a complete theory, it gives another stimulating direction in which to look for answers.

IV CAPTURED BY COMPLEXITY

> *“But to show him [i.e., man] another prodigy equally astonishing, let him examine the most delicate things he knows. Let a mite be given him, with its minute body and parts incomparably more minute, limbs with their joints, veins in the limbs, blood in the veins, humours in the blood, drops in the humours, vapours in the drops. Dividing these last things again, let him exhaust his powers of conceptions, and let the last object at which he can arrive be now that of our discourse. Perhaps he will think that there is the smallest point in the nature. I will let him see therein a new abyss. I will paint for him not only the visible universe, but all that he can conceive of nature’s immensity in the womb of this abridged atom. Let him see there in the infinity of the universes, each of which has its firmament, its planets, its earth, in the same proportion as in the visible world; in each earth animals, and in the last mites, in which he will find again all that the first had, finding still in these others the same thing without end and without cessation. Let him lose himself in wonders as amazing in their littleness as the others in their vastness. For who will not be astounded at the fact that our body, which a little while ago was imperceptible in the universe, itself imperceptible in the bosom of the whole, is now a colossus, a world, or rather a whole, in respect of the nothingness which we cannot reach?”*[129]

While in the previous chapter we spoke about the *process* of creating complexity, we are now going to focus on some of many examples of particular complex systems. In the sequence of problems, as stated at the beginning of the chapter III, we have passed on to the third one, i.e. *where* one can find complexity. Those readers that have followed our text up to this point probably already know what the answer is: it is simply *everywhere*.

Since quite a lot has already been said about general complex systems, we prefer to restrict ourselves to only two particular examples of

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[129] Pascal, B. (1931) „The Relativity of Magnitude“, from *Pensées*; transl. by W. F. Trotter, Dutton, New York.

places where one can meet complexity. There are many complex systems, so it should not be a problem to choose two of them and to put them under scrutiny. However, for our purposes, we need something different. First, we need to inspect the area of microscopic particles whether one could find some good examples of complex systems.

As far as we know this idea is rather original, because most proposals speaking of complexity in the connection with the quantum world only try to show that complexity might have its origin in quantum laws, and implicitly that quantum mechanics can be regarded as its source. However, the idea that not only quantum world as a whole but that even individual quantum systems can be to some extent be regarded as complex systems is new, and for some of our readers certainly daring as well. In the next section we will try to show that such a stream of thinking has good sense and even can be fruitful.

Despite the fact that a great number of complexity definitions have been proposed (see Chapter II) no one has said what the exact smallest size of a general complex system should be. The reason is twofold: on the one hand because no unambiguous and exhaustive definition of complexity exists, and on the other hand, it is already well known that size is not among the main characteristics of complexity.[130] The only attempt in this direction that we know of belongs to Robert Rosen, who asserts that: “complexity is the basic feature of the world… from the atomic level on…” (Rosen, http, cf. Chapter II). So why not to try this path?

The second system we have chosen is more traditional but perhaps not expected in a paper of the kind that presents itself as dealing primarily with conclusions coming from the natural sciences. The example is language, and we have decided on it because it represents a common example of a non-physical complex system. Then, together with the content of previous chapters we will cover almost all main domains of the world we live in and it will confirm to us that one can really find complexity everywhere. And, what is even more important, it will open a door for us to search for a common theory

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[130] Let us commemorate the truism that a big thing can be simple, e.g. a sand-rock formation or complicated, e.g. a plain, but a small thing can be pretty complex, such as a living cell for example.

or at least a common language that one could use in complexity studies, regardless of the particular subject.

1. Complexity in the quantum world

Some readers will probably find what we are going to propose ridiculous. For we will propose a rather unusual connection between quantum systems, i.e. very small systems, and complex systems, i.e. very complicated and traditionally considered as “big”. Our proposition is as follows: *quantum systems have some of the features of general complex systems*. For this moment let us accept this statement and have a look at quantum objects. What do we actually know about them?

The typical objects that quantum mechanics deals with are atoms,[131] or at best, with clusters of atoms, i.e. molecules – though giant biological ones.[132] The word “atom” comes from Greek “atomos” and means “indivisible” – from, *a-* for “not” and *tomos* for “cutting”. It was first used by Democritus[133] and it gave a name to a whole philosophical school, called atomism. Atomism was born on the basis of Parmenides’[134] thesis that there is no difference between things, neither change nor plurality, because one being is no different from another being.[135] Leucippus and Democritus, for their part, placed the unity postulated by Parmenides into the homogeneity of the prime matter that exists in an infinite number of small atoms, mutually separated by non-being, i.e. space. Atoms are further indivisible, they differ only by their shapes and they move around along arbitrary trajectories. They can collide and combine; new combinations can, however, disintegrate again.[136]

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[131] Some people surely would not agree with this statement, because the definition of the borders of the quantum world is rather disputable; it is certain that we are able to count the atoms of hydrogen exactly, but not much more.

[132] Now it is even possible to count some parts of DNA molecules.

[133] (460–370 B. C.)

[134] (* 510 B. C.)

[135] According to Leo Elders (Elders 1997: 40)

[136] Cf. Aristotle, *De gen. et corrup.* 325a23 nn.

Despite its great inventiveness, this concept was forgotten in the course of time, and only revived by Dalton,[137] whose early studies on gases led to the development of the law of partial pressures (known as Dalton's law; *q.v.*), which states that the total pressure of a mixture of gases equals the sum of the pressures of the gases in the mixture, each gas acting independently. He also devised a system of chemical symbols and, having ascertained the relative weights of atoms (particles of matter), in 1803 arranged them into a table. In addition, he formulated the theory that chemical combinations of different elements occur in simple numerical ratios, by weight, which led to the development of the laws of definite and multiple proportions. Finally, he developed his masterpiece of synthesis – the atomic theory; the thesis that all elements are composed of tiny, indestructible particles called *atoms* that are all alike and have the same atomic weight.[138]

Now, everybody already knows that the truth about atoms is a bit different. They *are* divisible and what is more, even some of their components are composed of other components, e.g. protons and neutrons from quarks. People nowadays are more careful to declare something as “the last piece of matter, further indivisible”. Experience has shown that the reality of matter is rather tricky and much more complicated than one could even have imagined only few years ago. At present we know the whole long list of sc. elementary particles that are subject of particle physics. However, physics also deals with other “kinds” of physical micro-objects. For example, with quantum waves, which are the subject of quantum field theory[139] or, with superstrings, which are considered to be promising candidates for explaining the final composition of matter and the universe as a whole.[140]

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[137] (1766–1844)

[138] As it turns out, atoms are themselves made out of smaller particles. In fact, almost all of an atom is empty space. At the center is a tiny positive nucleus composed of nucleons (protons and neutrons), and the rest of the atom contains only the fairly flexible electron shells. Usually atoms are electrically neutral with as many electrons as protons. The simplest atom is the hydrogen atom, having the atomic number 1 and consisting of one proton and one electron. It has been the subject of much interest in science, particularly in the early development of quantum theory.

[139] This distinction is, however, not real since elementary particles are actually considered as quanta of fields.

[140] Superstrings are considered to be an alternative approach to describing the microworld. They are often wrongly characterized as being “smaller” or more fundamental than microparticles themselves. However they actually have a completely different meaning: they represent all particles concurrently. For further reading see Greene, B. (2000) *The Elegant Universe*, Vintage Books USA.

Since quantum physics itself does not know what exactly its subject is – this may sound ridiculous, but it is one hundred percent true – and since the ontology of micro-object is an extremely difficult task, far from being solved, we will reduce our object of interest, when speaking of *quantum systems*, into *"something" small bearing a sufficient number of general properties of most quantum systems,* easy to imagine, let us say a hydrogen atom, atomic nucleus, electron, photon etc.

In the previous paragraphs we have already came across the first attribute of quantum systems, i.e. their *hierarchical structure*.[141] To repeat what has been already said and to give one particular example: an atomic nucleus is composed of protons and neutrons that are composed of quarks. And there is still the chance that quarks are not the last stage on the way down to the deepest layers of matter, but that there is something even "smaller"[142] continuing ad infinitum.

At this moment some of our readers could object to the idea we are proposing here and argue that this comparison is rather vague. Ordinary complex systems are always considered as composed of large numbers of elements – from the smallest ones up to the biggest – while quantum systems are themselves only small. Moreover, we do not even know what the components of the particular quantum object are and their number can be only guessed at.

These arguments are certainly valid, but not strong enough to force us to abandon our hypothesis. As we saw in the foregoing text, the number of constituents is not crucial for designating a complex system. What is more important is the non-trivial relationship between these elements, and the hierarchy of the whole. And this is a condition that is – at least to some extent

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[141] At this point many physicists would probably disagree for they "do not like" talking about scale and hierarchy in connection with quantum mechanics. They cope at best with the division of sc. matter particles and interaction particles. In other words, they distinguish particles that represent matter constituents and particles that mediate physical interactions.

[142] We use quotation marks when speaking about size in the microworld, because even this – in the ordinary world a common and clear term – loses its meaning. In principle it is impossible to define what is "bigger" and "smaller" on the micro-level. This very interesting physics/philosophical problem does not, however, fall within the main topic of our article.

– fulfilled within quantum systems. The quantum world represents a subset of the whole world, and is definitely complex.[143]

Another interesting and typical feature of quantum objects is the impossibility to determine their boundaries. The idea of electrons as blue bullets circling round the nucleus was abandoned long time ago. Now we speak of “clouds” or a vibrating and quivering “something”. Who hasn’t heard of the “soup” of microparticles our world is composed or – mystically – about “dancers” dancing their magical dance somewhere on the deepest ground of our reality.[144] Although this concept is probably not any nearer to reality than the others, it expresses the intricacy of quantum world better. It is a step away from rough simplification – although still a very small step.

In Chapter II, section 3 of our treatise we distinguished between two distinct categories of components forming a complex system, i.e. parts and pieces. If you remember we defined pieces as things “with boundaries that can be traced”. Since this condition is *not* fulfilled in the case of microparticles in any manner, we must conclude that quantum systems are composed of parts. But this is the same conclusion as we drew when characterizing complex systems. So, it appears that we have found the second common feature, shared by complex and quantum systems.[145]

One of the cornerstones of the Copenhagen interpretation of quantum mechanics is the tenet that any observation or experiment performed on a quantum system always significantly changes its state. This is a strange predicate, but still acceptable. But this is not the end of “complicating” things in quantum world. The term causing trouble in this case is ‘state’. While in classical physics every quantity has its definite value, in quantum mechanics this is not fulfilled every time. Such fuzzy states of quantum systems is formally described as linear combinations, i.e. *superposition*, of the state

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[143] We purposely avoid introducing “big” and “small” complexity (analogous to big and small infinity) – an idea that might spontaneously enter the mind at this stage.

[144] One of the greatest gurus of such “quantum mysticism” is surely Fritjof Capra with his famous book *The Tao of Physics*, Fontana Paperbacks, London 1983.

[145] Moreover, there is another attribute of quantum objects causing headaches, mainly for philosophers: they do not have any distinct identity. Cf. for example reactions of the transmutations of protons and neutrons (p^+,n) and (n,p^+): $p^+ + e^- \rightarrow n + \nu$, $n + e^+ \rightarrow p^+ + \nu^{\sim}$.

vectors bearing the values of the given quantity[146]. And this is something that we do not meet in our ordinary everyday experience.

In 1935 E. Schrödinger formulated the *gedanken* experiment that was supposed to show that quantum states of superposition could be transferred up to the microscopic level (Schrödinger 1935: 807). It is the famous and already a bit defiled *paradox of Schrödinger's cat*. Imagine a cat (real and for the present alive) closed in a thick box. Together with the cat there is a vial of poison inside the box, connected to a clever release mechanism which releases the poison from the vial at the moment when the nucleus decay happens of the only radioactive nucleus embedded within the mechanism. The nucleus decay is ordered to quantum laws so that it is absolutely unpredictable. Moreover, in an instant when the nucleus is not observed it is in the state o superposition of states of the nucleus "not yet disintegrated" and "already disintegrated". Since the cat's life depends directly on the nucleus' history, the former can be considered as subordinate to the strange quantum laws, too. The poor cat will therefore get into the state of superposition of the "living cat" and "dead cat", too (cf. Müllerova 1999: 43).

To imagine such a situation is impossible for the common sense and a "pragmatic physicist" would say that to deal with the question of *what* the state of superposition is, is a kind of foolishness. However, what happens when we open the door of the box and look inside? The situation is clear at a single blow. Of course, it is not possible to see the cat in such a state of superposition. So, inside we would either meet a happy, living cat, or a dead cat's body. In the language of quantum mechanics, we changed the state of the cat by observing it.[147] Although the cat is a macroscopic object in our *gedanken* experiment, it impersonates the "prolonged" quantum object and as such it undergoes a change caused be the observer. It interacts with him or her that means that it must be open. Being open and having the ability to

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[146] In quantum mechanics we speak of observables rather than quantities. The reason is to stress the dependence on the experimental course.

[147] Perhaps it is better to say that we "selected" one of the possible states and brought it into the reality.

interact with its environment are other important characteristics of complex systems![148]

To proceed to another feature of quantum systems, which we consider as common to all systems (thus automatically to complex systems too) we will stick to the situation as described in footnote 151 for a while. Let us try to make a story from it: a man wearing a white mantle and thick glasses enters a room and approaches the optical table standing in the middle. He is carrying a semi-reflecting mirror. He fixes it on the table and looks at the photon's source standing on the opposite side of the table. When the mechanism is switched on, a big number of photons start being produced. One after another they are selected from the huge photonic cloud and released on paths towards the baited mirror. The first one flies along the table's surface, inevitably approaching the mirror's cold face. But, what happens? Contrary to expectations, it is not scattered back into the space in front of the mirror, but smoothly penetrates to the other side, where a photonic detector is waiting for it. When photons enter the detector, it confirms its arrival by a blink of its electronics giving a noise signal, too. Now the man in the white mantle knows that the first photon has succeeded in getting behind the mirror.[149]

This is a "physics" story, but as every other real story it takes place in the course of *time*. And this is the thing we would like to point out now. Although it is a matter of a fact that physics is still not comfortable with introducing time into its – not just as a parameter - into its formalism, it cannot be excluded (if we want to keep a realistic point of view).[150] Quantum systems have their histories analogically to all other systems that undergo change. But,

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[148] If someone does not like the "semi-classical" illustration as presented here they can easily stay within the framework of quantum systems and imagine a single photon delegated towards the mirror reflecting only part of the incident light, the rest can come through. So, there are two possible paths for the given photon that can be followed: one going through the mirror and the second scattering it back. Then, the photon "behind the mirror" will be in a state of superposition that can be expressed as a state of "being simultaneously on both paths". Only a proper detection device can say which situation has been realized, i.e. change the quantum superposition state into the classical one.

[149] We are well aware that this story is hardly realised in this manner, but to analyse the technical details of its realisation is not essential at this point. The inquisitive reader can address himself to many existing handbooks of quantum mechanics and optics.

[150] Actually, in quantum physics this situation is even worse. Although many attempts have been made to introduce time – strictly speaking the time operator – into the theory, no big successes have been reached. Some of the recently proposed approaches to this problem appear promising, with far-reaching implications and we will mention some of them in the next chapter.

this is nothing else than another common attribute of quantum and complex systems.

Now, we will move on to more epistemological issues. As we have already mentioned in the foregoing, we are never able to understand any complex system "as it is" but can only look at it from some particular point of view, i.e. through a given experiment. If one gets the idea to "have a look" at a photon, for example, one might encounter serious problems. Not even the thickest magnifying glass, nor can the most sophisticated microscope transmit its images in a manner suitable for the human eye.

The only thing we can really observe is the photon's manifestation in some medium or within some secondary instrument. We can bar its path with an optical grid or a device called a Photomultiplier Tube, commonly used for detecting photons. Both of these experimental options will give us information about the presence, or absence, of photons. But – and very important from the philosophical point of view – their results will differ in answering the question "what is a photon?" The output from the first arrangement would say "a wave," the output from the second one would object that "it is a particle". So – without any ambitions to seriously solve this contradiction – we can conclude that "ontological" questions searching for the *what-ness* of things are problematic in quantum mechanics. The questions dealing with our possible *knowledge* of quantum objects and the methodology that should be used when working with the quantum field appear more promising. Even though the characteristics that we used as an illustration of the joint attributes of quantum and complex systems could be considered to be doubtful by some, this last conclusion should be quite obvious.[151]

Before a physicist chooses how to observe it, an electron is neither a wave nor a particle. It is in some sense non-real, it exists in an indeterminate limbo. "Not until you start asking a question, do you get something," Wheeler said.; Every it – every particle, every field or force, even the space-time continuum itself – derives its function, its meaning, its very existence – even

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[151] More details supporting this conviction will be given in the next section devoted to language.

in some contexts indirectly – from the apparatus. “The it from the bit” elicits answers to yes-or-no questions, binary choices, bits.[152]

But, as if it where not enough that we can only derive “it from a bit” – paraphrasing Wheeler – there is another aspect that goes hand in hand with the act of observation in quantum mechanics, turning physicists’ heads: every time we try to “enter” the system and look at what is happening inside, we destroy it. The quantum object cannot “survive” the interaction with the experimental device we use. What we “see” in our experiment is *not* the same particle, for instance, as it was before entering our experimental set-up. This change of its properties is the inevitable result of our activities.[153]

When a photon enters a detector it undergoes a number of collisions with the particles constituting the detector’s vehicle. It looses its energy and implicitly changes its wavelength. The same also happens to other microparticles. This is an effect one cannot pass over since, in every macroscopic device – we have no other choice than to a use macroscopic device, since we ourselves are macroscopic – the number of such interactions is pretty big.

So, our man in the white mantle is now confronted with a new kind of problem. Not only must he handle the dual nature of the quantum entity he is observing, he must also allow for the fact that this entity is now different from what it was before. He is changing reality and it is running away from him. The *a priori* impossibility of grasping reality in its “original” state is something very frustrating in the work done on the quantum field.[154]

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[152] An interview with A. Wheeler, In: Horgan, J. (1996) “The End of Science, Facing the Limits of Knowledge in the Twilight of the Scientific Age”. Addison-Wesley Publ. Comp.; Cf. (1990) “Information, Physics, Quantum: The Search for Links” ; in: *Complexity, Entropy, and the Physics of Information*, ed. by W. H. Zurek, Addison-Wesley Reading Mass.

[153] Actually, the problem of mutual interaction between an observer and observed system is not limited to quantum mechanics. What distinguishes quantum mechanics from other physics is the value of $\hbar$ (reduced Planck’s constant) and the notion of minimal interaction at a level comparable to “size of $\hbar$”.

[154] It is quite interesting to realize that very similar problems can be found in completely different scientific branches. As typical a example one could mention zoology, inner medicine, neurobiology etc. Almost all research is actually *not* done on living beings, organs or cells – as it is supposed to be done – but on “dead” ones, because, there is no technique to look and “work” inside the living organism without killing it or at least significantly impairing it. However, a dead frog lying on a table in the lab is “the same” frog as it was when alive in a pool. Actually, what we do in most of our scientific efforts is to “steal” the nature from things. The Czech philosopher Zdenek Neubauer uses a nice pun in this context, playing with the Latin and Greek words for ‘nature’: “De-natura-tion of Physis”. (However, one should also point out that huge progress has been made recently in developing observation techniques that allow people to watch the living organisms without any crucial interventions, especially

2. The origins of structures in chemistry

One of the most important discoveries in the field of complexity reached in the second half of the previous century was certainly the fact that simple chemical reactions can spontaneously create patterns in time and space when transferred into a non-linear regime. They can move or stay in one place, and they are created by mutually interconnected sequences of chemical reactions and by the diffusion of the chemicals involved. The size of a new chemical pattern depends on the composition of the initial chemical cocktail, and on how far from the equilibrium this cocktail finds itself.

The formation of these non-linear patterns was first predicted by Alan Turing in 1952 in an article published in *Philosophical Transactions of the Royal Society*, vol. B (cf. Coveney 1995). At that time he worked at the University of Manchester and was interested in the problem of *what the chemical nature of the formation of shape, structure and function in living beings is* - in biology this process is called *morphogenesis*.

He made a fascinating discovery: non-linear effects in a soup of chemicals can lead to the emergence of space patterns when a number of colour chemicals with different coefficients of diffusion mutually react. This finding is quite contrary to what one would expect. Intuitively the expected result would be as follows: any irreversible mixing process will destroy already existing patterns or structures, in the same manner as the white lines of milk finally disappear when we pour it into the black coffee. What a surprise then, when it appeared that the result was different!

On the basis of these results Turing later formulated the hypothesis that stationary patterns can be created by a following process: two reagents exhibit different velocities of diffusion and the faster ingredient inhibits the reaction, while the slower ingredient catalyses it. Stationary patterns start to emerge at the exact distance from the state of equilibrium – a bifurcation point – which is called Turing's instability.

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in the study of brain activity. We can also mention RTG microscopy, using lasers to get images of living cells, for example.)

Nearly at the same time as Turing stated his predictions about the self-organisation of chemicals due to processes of reaction and diffusion in a state far from equilibrium, a Russian chemist, Boris Pavlovich Belousov, created the first example of a real reaction that supported ideas of Turing. His results were so “strange” that it took another ten years until the scientific community was ready to seriously consider it.

During the 1960`s Belousov`s oscillating mixture was studied by another Russian chemists, Anatolij Zhabotinsky. He succeeded in repeating Belousov`s former experiment, and to get even more interesting results. He attracted many other people to this field of study, and since then the research of self-organised chemical reactions has become a modest domain.

The reaction originally discovered by Belousov, and many of its later variants, is known as the *Belousov-Zhabotinsky Reaction* (BZR). A mixture of chemicals in the BZR creates an excitable environment, i.e. an environment that can change its state when influenced by stimuli stronger than a certain minimal value. After excitation such an environment becomes inert (it stops responding) and returns back to its initial sensitive state, via states that can themselves be excited. One example of such behaviour can be seen in the spiral waves produced by a heart muscle. Actually, the analogy between BZR and the behaviour of a heart muscle is now considered as proven without doubt.

On the other hand, to find a chemical cocktail that would correspond with Turing’s prediction of stationary patterns is much more difficult. The reason is that conditions for the formation of Turing’s patterns are very limited. They demand some kind of a positive backward-relation such as autocatalysis, for example, and the presence of two chemicals called the activator and the inhibitor. Using such systems one can also get behaviour quite similar to the behaviour of living beings.

3. The complexity of living organisms

Walter M. Elsasser says (Elsasser 1966: 103) that one of the most characteristic features of organisms, perhaps their most outstanding one, is their utter complexity in *structure* as well as in *function*. In other words, a basic aspect of biological relationships is *intrinsic and irreducible logical complexity*.

Clearly there are innumerable processes in the organism, which can be understood in terms of mechanistic models. This is the method that *mechanistic biology* uses. Analogically, mechanistic biological philosophy tries to reduce the complex behaviour of the organism to the much simpler laws of physics.

A completely orthogonal approach is that of *vitalism*, which tries to explain organisms in terms of the quasi-physical concept of a superadded vital force.

When we talk about ‘living’ organisms we should first put a question: What is life? To define life is a very difficult task. According to one dictionary definition “life is a property shared by living things that distinguishes them from the non-living things”, according to another it is “a state of being alive”. These definitions are rather vague. To give an exhaustive and exact logical definition of “being alive” is still just a dream. Scientists can at best name a number of features that most living beings have in common, and complexity is certainly among them.

As we saw in chapter III, complexity is closely connected with *self-organization*.[155] For the most characteristic feature of self-organization is the existence of non-linear feedback, and life could emerge with the emerging of a molecule (or molecules) that is self-replicating and catalyses its own production. The most famous molecule of this kind is definitely DNA, which is therefore considered as a basic building block of life.

But DNA itself is not yet alive in the proper sense of the word. The first “material” representing a bridge between non-living molecules and living cells is the gene, i.e. self-propagating material that carries information.

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[155] We discussed the phenomenon of self-organization in the previous chapter.

Feedback loops are the most fundamental element of all biological processes, encompassing a huge number of activities starting from the energetic metabolism of cells and ending with organization of complicated processes. All plans for such feedback-processes are contained in the genes that are responsible for the successful reading and decoding of the instructions. Operations taking place in organisms are thus highly non-linear, leading to complexity.

The feedback processes proceeding inside plant and animal cells are necessary for generating a physiological order enabling life. There are also known examples of space pictures inside cells where self-organization manifests itself. According to all indicators, biological phenomena are caused by non-linear mechanisms.

More advanced organisms contain billions of cells that, in the course of their evolution, are organized into highly sophisticated structures. Peter Coveney and Roger Highfield (Coveney 1995) give the beautiful example of strange creatures called grindelia (*Myxomycetes*).

Grindelia are something between a set of individual cells and an organism. Sometimes they create a many-celled body (about 100 000 cells), while at other times the cells wonder independently one form another. Grindelia feed on bacteria. When there is enough bacteria, the individual cells insatiably fix on it and do not care for the others. They reproduce through direct cell division. Eventually, however, the colony will start to suffer from a lack of food; at that moment the individual cells start to “notice” one another. Due to some unknown non-linear processes some of the cells in the colony take over a leadership position of keeping a rhythm and transmit signals – using some chemical compound – that the food is finished.

After a few microseconds the cells start to change their positions and move towards such centres of information. They multiply this information and propagate it further – this is a form of a feedback mechanism, which leads to the situation that more and more cells move closer to these centres.

The whole mass of cells organizes itself into a kind of multi-cell “slug” with a head and a tail that wriggles as it searches for light and water. It takes a few hours for cells to create this simple organism. It is 1-2 mm long and crawls, guided by the pulsing source placed on the tip. It reproduces by spores that are created in a tough spindle with a cap; when spores are ready, the cap breaks and spores spread far and wide. . Now the whole cycle can start from the beginning again.

Nature disposes of mechanisms that organize cells into enormous varieties of forms and shapes. A full understanding of this mechanism is, however, still unknown to us. Some hope is provided by the fact that a complex system such as *Homo sapiens* is to some extent ruled to by the same genetic program as other plants and animals.

In the same manner that living beings organise themselves into structures, whole communities of living beings create structures of the highest scale. The organized structures of animal's communities occur. One can mention for example community of bees, ants, termites, etc.

The idea that communities of insects behave as super-organisms is not new. Moreover, this stream of thought has not limited itself to particular animals, but has even been applied to the totality of organisms. In 1968 James Lovelock shocked his readers with the proposition that whole earth is one huge super-organism, where living creatures, rocks, air and water influence one another in complicated ways; it is through this that the stability of the environment is assured.

4. The formation of structures in biology

It has long been known that small, light animals move fast, while big and heavy ones move slowly. Connected to this is the heart frequency, which is certainly much higher with a mouse than with an elephant. The latter, however, lives much longer. Thus, is there any connection between life-duration or 'activity' and body mass?

'Activity' can be compared with the velocity of the mass exchange within an organism. This is represented by the quantity called the rate of metabolism. It appears that there really is some relation between the biological variable X – e.g. the rate of metabolism, or the duration of the life of an organism – and body mass M. Using a mathematical formula it can be expressed as follows (Richter 2002: 64):

$X = X_0 \,.\, M^{\gamma}$,

where X_0 is a constant varying according to the kind of organism and γ is an index scaling the metabolism rate. The reason for this relation was recently explained with the help of the fractal characteristics[156] of organisms (West 1999: 1677). Their hypothesis is based on the following three principles:

1. The pressure of natural selection in nature leads towards the optimisation of the capacity for mass exchange of a living being, through the maximization of its surface – mediating the mass exchange – and through the minimization of the distance and time of transport within the organism.
2. The inner in net connected providing tools of the organism can have a fractal structure.
3. There is the smallest typical length in biological systems, which is not scaled according to the size of an organism, but remains the same.

Principle 1: the maximal surface builds a fractal, filled with a volume. On the other hand, the minimal transport-lengths are normal geometrical trajectories that have nothing to do with fractals. West (1999: 1677) proposes

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[156] Fractality is a mathematical concept that seems to fit some structures in nature. Numerous scientists use derivatives of this concept, and therefore it is bound to happen that the term 'fractal structure' is used with different meanings. It is either used to denote the fractal set itself, or the generating system of the fractal set, where the generating system is based on a suitable construction rule that usually works inductively from one generation level to the next.

Historically, F. Hausdorff (1919) introduced the term fractal-dimension in the sense of a non-integer dimension, and along with the given definition, the age of fractality was born. Consequently, a set that can be assigned a fractal dimension is called a fractal set. One can determine the fractal dimension of the set by observing the optimal covering systems of fractal sets with decreasing diameters. It should be mentioned that several different definitions of fractal-dimension were created since Hausdorff's paper and their relations are not simple. Except for self-similar sets, most of these definitions lead to the same dimension number.

Looking at the properties of fractal sets more generally, they can be considered as boundary sets that connect (or divide) neighbored systems. Approximations of such sets can be observed in the real world, for example in coast lines, rough landscape surfaces, or in the "endpoints" of some bronchial or vascular trees.

that while living beings act in a three-dimension space, their inner physiology runs in a four-dimension space. The fourth dimension of life is then represented by fractals. Thus, when one deals with biological systems one should abandon traditional Euclidean geometry and use another way of scaling, based on fractal geometry.

This idea is still quite contentious, but represents another interesting and promising approach to dealing with intricate biological systems, and implicitly with complexity itself.

5. Intelligent materials and non-trivial machines

Intelligence is certainly considered as one of the attributes of living systems and since all living systems can be counted as complex systems, intelligence is closely connected with complexity. Although ‘intelligence’ as we normally understand it is a quality associated with higher life-forms, lately it is also frequently connected with materials objects, i.e. non-living things. How is this possible?

It is true, as Prof. Gerd Müller from the Faunhofer Institute for Silicate Research ISC in Würzburg says in his article (Müller 2004: 14), that intelligence implies conscious perception and deliberate acts, and most importantly the ability to make decisions when faced with a number of different options. ‘Materials’, by contrast, are the epitome of lifelessness. So what do we mean when we juxtapose these two diametrically opposed ideas? It is also true that the degree of intelligence possessed by different (living) individuals is a widely variable attribute, despite the considerable length of time the human race has been in evolution. For this reason, Prof. Müller stresses, scientists should be careful not to exaggerate their claims of having imparted intelligence to lifeless materials.

A good example of such ‘intelligent’ materials, are the phototropic lenses and coatings used in ophthalmology. They automatically adapt their optical filtering properties to the intensity of light falling on them, becoming darker in bright sunlight and lighter in the shade. In other words, they capture signals from their environment (as a sensor) and act in response to these signals (as an actuator). Admittedly, this action is not based on any conscious decision; it is merely a reflex, but nevertheless one that makes sense.

When materials are deemed to be “smart” by virtue of their ability to produce a mechanical response to changes in external parameters such as electric or magnetic fields or temperature, they are often expected to do more than carry out functions as a sensor or actuator, leaving the task of converting the sensed input into an actuating signal to external controllers and power supplies.

Materials used in this way, in conjunction with a self-learning control element, are referred to as “adaptive materials”, and the complete unit is referred to as an “adaptive system”. The most advanced materials in this category are probably the piezoelectric[157] and electrostrictive materials – mainly ceramics but also some polymers. These materials work by converting mechanical deformations into signals, or conversely by changing their dimensions in response to an applied electric field. Besides these, other materials can also be mentioned that change shape in response to magnetic fields (magnetostrictive alloys) or heat (shape memory alloys). The latter are already being widely used in thermosensitive switches.

Piezoelectric materials function on a principle similar to living organisms, in that they produce movement in response to electrical, or in the latter case electrochemical, stimulation, but they require much higher field strengths and voltages, by several orders of magnitude.

When talking about materials, the tendency is to think in terms of solids, while liquids are considered more as consumables or processing fluids. But it would be perfectly justified to regard electrorheological and

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[157] Piezoelectricity is the coupling between a material's mechanical and electrical behaviours. In the simplest of terms, when a piezoelectric material is squeezed, an electric charge collects on its surface. Conversely, when a piezoelectric material is subjected to a voltage drop, it mechanically deforms. Many crystalline materials exhibit piezoelectric behavior. A few materials exhibit the phenomenon strongly enough to be used in applications that take advantage of their properties. These include quartz, Rochelle salt lead titanate zirconate ceramics, barium titanate, and polyvinylidene flouride (a polymer film). On a nanoscopic scale, piezoelectricity results from a non-uniform charge distribution within a crystal's unit cells. When such a crystal is mechanically deformed, the positive and negative charge centres displace by differing amounts. So, while the overall crystal remains electrically neutral, the difference in charge center displacements results in an electric polarization within the crystal. Electric polarization due to mechanical input is perceived as piezoelectricity. From an engineering or modelling point of view, piezoelectricity results in a change to a material's constitutive properties. Many finite element codes include piezoelectric modelling capability.

magnetorheological fluids - which can increase their viscosity many times over in the presence of an electric or magnetic field – as smart materials, for they too are capable of functioning as actuators, for example in dampers and valves, and even theoretically as sensors for use in external control systems.

The progress in computer science and information technology over the last few decades gives reason to question the belief that human beings have a monopoly on intelligence, according to Prof. Müller (Müller 2004: 15). Materials still lag a long way behind this respect, but systems based on smart, adaptive materials, with integrated sensors and actuators, backed up by external data processing and control elements, will soon be able to carry out a multitude of functions with a lower input of mass and energy than it is possible at present.

One step further than the intelligent materials brings us to the problem of *trivial* and *non-trivial* machines – a distinction formulated by the cybernetic Heinz von Foerster in the terms of Alain Turing [158] A trivial machine is a machine whose operations are not influenced by previous operations. It is analytically determinable, independent from previous operations, and thus predictable. For non-trivial machines, however, this is no longer true, as the problem of identification, i.e., deducing the structure of the machine from its behaviour, becomes unsolvable. This distinction is often considered a starting point from which to recognise the complexity of cognitive behaviour.

Most of the machines we construct and buy are certainly trivial machines, since we expect from a toaster to toast, a washing machine to wash, a motorcar should predictably respond to its driver's operations, etc. In fact, all our efforts go in one direction: to create trivial machines, or, if we encounter non-trivial machines, to convert them into trivial machines. However, there are also enthusiasts who focus on creating non-trivial machines and many of them have been brought to life.[159]

Even though talking about ‘smartness’, ‘intelligence’ and complexity itself in connection with materials and machines is still rather metaphorical it points out one fundamental aspect of the problem: We must be very careful

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[158] Foerster, H. von, Poerkesen, B. (2003) *Understanding Systems Conversations on Epistemology and Ethics*, Kluwer Ac. Publ.

[159] The reader will find more facts in the next chapter.

when dividing systems into different categories according to their “rate of intricacy or complexity” and be aware of the fact that such “simple things” – that we would automatically label as “non-trivial” – can surprise us. Moreover, it seems that we find ourselves somewhere in the course of the process of developing and knowing the depth of non-living objects, and in a few years it might be quite natural to consider some particular kinds of materials and especially machines as being complex systems.[160]

6. The complexity of language

According to Teresa Satterfield from the University of Michigan “language is a complex endeavour: how we acquire language as children, how our brains make (and make sense of) language and how languages change over time” (Satterfield, http). This is a view on which most linguists as well as complexity scientists would agree. Differences come either in the treatment of the problem of whether language is an innate capacity[161] – or humanity’s masterpiece – or with the problem of how to put the complexity of language into a “scientific” framework; how to deal with it rigorously, so to say.

Some presentation of the complexity of language can be found in many works. It is a rewarding topic for everlasting disputes and speculation. Language is an open and “living” system where one can always disclose something new, providing a huge space for playing the game called ‘research’. One nice demonstration we have found in lecture notes of Prof. Zeljko Boskovic from Department of Linguistics, University of Connecticut (Boskovic, http). Prof. Boskovic sees proof for the complexity of language in the fact that we are able to use our native languages – which we learned as children – even though we have not been taught much theory about them. However, as he stresses, even the simplest things about language are very complex!

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[160] To be the case these materials and machines should fulfill the following criteria (see chapter II): they should be open to the changes coming from their environment and respond properly to them, be able to evolve in time, be sensitive to some “outer” cause working on them and at least to reproduce.

[161] Cf. Chomsky, N. (1972) *Language and Mind*, New York: Harcourt Brace Jovanovich, Inc..

See the following example (presented by Prof. Boskovic) showing how we form *yes/no questions* in English.

(1) Students are smart.

(2) Are students smart?

If you are a child learning English you could hypothesise that to form a yes/no question in English you take the second word in a sentence and move it to the beginning of the sentence, but this will give you the wrong result. See the following pair:

(3) Older students are smart

*(4) * Students older are smart?*

Sentence (4) is ungrammatical, we need to say:.

(5) Are older students smart?

Given these data, then the child could hypothesize that to form a yes/no question you take the auxiliary verb and move it to the beginning of the sentence. Let's see if this rule works:

(6) Students are thinking now that linguists are smart.

Since the rule that we are entertaining does not say anything about which auxiliary to move, then we could get:

*(7) * Are students are thinking now that linguists smart?*

We see that (7) is a bad sentence. The correct way of asking the yes/no question for (6) is:

(8) Are students thinking now that linguists are smart?

Given the data above, the child would have to change her hypothesis to the following: take the auxiliary at the beginning of the sentence and move it to the left. Let's see if this works.

(9) Students who are studying linguistics are smart.

If we move the first auxiliary to the front we would get (10), which is a bad sentence:

*(10) *Are students who studying linguistics are smart?*

The right way of asking the yes/no question for (9) is:

(11) Are students who are studying linguistics smart?

As we see figuring out the rule of yes/no question formation is very complex. However, children do not try all the different possibilities we have tried above. The fact that they never produce sentences such as (4), (7), (10) is evidence that children never entertain the hypotheses that we have entertained here. Children know something that we don't when trying to figure out how language works. This knowledge is innate knowledge of language.

Ambiguity

Here is another example of knowledge of language in the absence of experience. Notice the following sentences:

(12) Mary had a lamb.

(13) Mary had a little lamb with some potatoes.

(14) Mary had a little lamb and the doctors were surprised.

The examples above show us that the verb "have" can mean different things: to possess, to eat, to give birth.

Another case of ambiguity comes not from the meaning of words but from the way you put words together in a sentence. Notice the following examples:

(15) Visiting relatives can be boring.

(16) Mary saw a man with binoculars.

Sentences (15), (16) are all ambiguous, they can all mean two different things. Nobody taught you this, and you still know it, you, as a native speaker of English, can tease apart the two meanings. How do you know this without explicit instruction? As we have seen this knowledge must be given, it is innate.

Below we will look at another example of knowledge in the absence of experience.

Notice the following question, which has two possible answers:

(17) Who did the coach want to shoot at the end of the game?

Answer 1: The coach wanted Mary to shoot at the end of the game.

Answer 2: The coach wanted to shoot Mary at the end of the game.

Now notice how this ambiguity is lost when we use "wanna", instead of "want+to".

(18) Who did the coach wanna shoot at the end of the game?

Only possible answer: The coach wants to shoot Mary.

This knowledge was not taught to you, it is knowledge that you bring with you; it is part of your innate knowledge of language. Here is another example of knowledge in the absence of experience. Note the following examples:

(19) After she came back, Mary studied linguistics

(20) She studied linguistics after Mary came back

(21) Mary studied linguistics after she came back.

In (19) "she" can refer to "Mary" or to someone else. In (20) "she" cannot refer to "Mary, but it can refer to someone else. In (21) "she" can refer to "Mary" or to someone else. This is something that you were never taught by your parents or English teachers. Yet you know these things. Think about what it would take to know these things. You would need to be explicitly taught this, given the relevant examples, and explained the meanings of the sentences in (19)-(21), but this does not happen; you know this because it is part of your innate knowledge of language.

“We have seen that there are things about language that you know and those things could not possibly have come from outside. They come from inside, from your innate knowledge of language, from your LAD”, Professor Boskovic writes and adds: “When linguists talk about this they say that ‘experience underdetermines the knowledge of language’. We know that knowledge of language cannot simply come from experience because our knowledge of language is much larger than our experience (our language input). This argument is called by linguists the ‘Poverty of the Stimulus Argument’.”

The difference between the child’s innate linguistics skills and the knowledge he or she acquires from the experience in the world (Satterf, http) is studied by Theresa Satterfield. She is interested in how these two components interact to produce the child’s native language. As is the case with studying other complex systems, her research is also mostly done on computers, using computer modelling. She simulates different conditions of the child’s environment, while either keeping the presupposed natural linguistics skills fixed, or varying them.

Not only is language as a whole a “difficult problem”, but even the words themselves present difficulties. Words are signs and their meanings are established by convention. Words are always tied to concepts, thoughts and ideas. This is verified with the existence of ambiguity when it comes to the meaning of certain words, which probably occurs in all languages.[162] This is such a common phenomenon that it entered the science of linguistics, and it posses a constant position in the theory. Thus we distinguish between *synonyms* and *homographs*. Synonyms are words that are graphically different – and also sound different – but express the same thing. For example: stones & rocks. In English the two sentences ‘The wall was made of stones’ and ‘The wall was made of rocks’ have the same meaning, and so one can choose between these words arbitrarily.[163] Homographs, on the other hand, sound and look identical, but express completely different things. For example: ‘I could not bear to give my pet bear to a zoo’ or ‘Even in the light of day, the light plastic table looked identical to the heavy wooden one’.

Nevertheless, these are not the only ‘problems’ with using words. If that were the case one could conclude that knowledge of English is non-trivial, but

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[162] This is the reason why the use of ordinary language is so problematic in natural sciences, where accuracy and unity of statements is required. As a result natural sciences – especially physics – departed to logic as a replacement for common language, or at least it uses the strategy of giving exact definitions of all terms used in a text or speech. And this is one thing that distinguishes the natural sciences from arts, for instance.

[163] Since English is not my native language to give the correct examples I had to consult Internet. All of the examples given are from the internet and thus not my own.

"not by much". English, as with all other modern languages, evolves in time. Some words are used less and less frequently as the objects they describe loose their meaning in people's life. Who uses the word 'washboard' these days? Most children probably do not even know what this word means. And on the other hand, would the people of the 19th century have understood the meaning of 'washing machine'? (A century before that they would not have understood the word 'machine'!)[164]

Language is not only ambiguous when it comes to choosing words, but also in its subjectivism. See for example the common word 'dog'. We all know what this word means. At the point of assigning this word to the particular object from the world we will probably all agree. The situation will, however, change rapidly when we also start to consider the associations this word calls up in different people. Some of them love dogs and start to think of nice things connected to these animals. Some of them might hate dogs and start to feel bad by only hearing the word. Many people will stay indifferent, because the word has no emotional content for them, etc. Since the use of language is no doubt much more than putting words in order according to grammatical rules – as a computer would do it – it is a very intricate affair. In addition to the brain's abilities that are peculiar to mankind, it requires experience: both personal and social.

A different situation can be found with 'terms' whose meaning is usually given by definition. The power of terms also consists in the fact that they are able to move through time and even through different languages without loosing or changing their content. Their meaning is given by definition and the definition does not change. One can give many examples of such terms: mass, velocity, cell, mammal, molecule, linear equation, etc.[165] Moreover, these definitions can be translated into arbitrary languages and then the

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[164] However, one does not have to move in time when one wants to introduce such examples. The same situation would certainly be realised when one brings a washing machine to people living away from civilisation in the middle of nowhere in Africa, Asia or South America and giving them the energy supply and teaching them how to use it. This idea might sound ridiculous, but it would result in the changing of their native language as well.

[165] Terms are naturally connected to sciences. In the natural sciences the situation is quite clear. Problems start with the arts, where exact definitions are rather rare. How should we define 'true' – one of the first philosophical terms? Or 'existence'? There are nearly as many definitions of these terms as there are philosophical schools. However they are still terms, not "common" words.

proper notion that represents it best can be chosen. On the other hand, there are terms that are usually not translated, such as ‘atom’ for example.

The fact that reality and language are closely connected has led to many philosophical disputes. The main question is whether words have some positive meaning or not. And, whether it makes any sense to speak about these things at all, seeing that other people will understand us and that we are able to express what we want to express. But, this is another subject that would require an independent treatise.

Another amazing topic in linguistic complexity research is evolutionary studies of new languages arising from prolonged contact between distinct languages. The well-known example is the Creole language, originating from English and African language-based Jamaican Creole. Using computer modelling Dr. Satterfield is able to simulate how aspects such as “social contact” and “innate linguistic capacities” link together.

With the help of a computer program she is able to “build” a society where a historically plausible language-contact scenario is reconstructed – as she describes it. This society is constructed quite realistically, composed of individuals such as slaves and slave-owners, all equipped with their own age, gender, race, ethnicity, social status, etc. over a lifespan. All of them are endowed with a language faculty, composed of a lexicon and grammatical modules operating on lexical items. The computer is able to simulate the dynamic interactions between speakers, and to track each person’s linguistic developments. As a result she can show how in Creolist literature Creole has grown, exemplifying the adaptability of the language learning process.

So there is not much doubt that language is a complex system evolving in time, however, not it is not man-made, but natural and innate to people. Steven Pinker is in accord with this view:

“Language is not a cultural artefact… Language is a complex, specialized skill, which develops in the child spontaneously, without conscious effort or formal instruction… For these reasons some cognitive scientists have described language as a psychological faculty, a mental organ, a neural system, and a computational module. But I prefer the admittedly quaint term ‘instinct’” (Pinker 1994:18).

Now the question is: Are all natural languages equally complex, or can there be some differences in their complexity? Usually it is accepted that the answer to this question is ”yes”. However, as the *Conference on Complexity in Language,* held in Paris, September 8, 1998 indicated, the matter is not so straightforward. It seems, for certain subsystems of language at least, that there may well be differences in complexity. Especially in Creole studies, as mentioned above, simplicity and complexity were implicitly dominant issues in the debate.

According to André Grüning from the University of Leipzig all natural languages exhibit surprisingly many similarities on an abstract level.[166] Thus there should be a possibility to construct a measure of their complexity in pure mathematical terms. Recently, much effort has been dedicated to this matter. The use of the sc. *Kolmogorov complexity* has been found to be very promising (Li 1995: 398; 1997).

Kolmogorov complexity is a measure of randomness, dealing with the quantity of information in individual objects. In other words, the Kolmogorov complexity of an object is the length of the shortest computer program that runs on a computer and produces that object as output. It was named after famous Russian mathematician and computer scientist Andrey Kolmogorov who proposed it in 1965. There was no doubt that it was a groundbreaking work, since it allowed for the quantification of the randomness of individual objects in an objective and absolute manner.[167]

By ‘object’ is meant something that can be described by the ones and zeros in computer language. Also, a computer program must be fixed because the program length can vary depending on the language. The fundamental result of Kolmogorov complexity is that nearly every object is complex (cf. Harfist: http). Objects with high Kolmogorov complexity are random, however there is also the possibility to analyse the complexity of finite sequences.

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[166] Cf. Chomski, N. (1979) *Lectures on Government and Binding*, MIT.

[167] Unfortunately, it turned out that the original definition is not good for this goal (in particular: to define what a random infinite sequence is). To get a correct definition of an infinite binary sequence one needs to consider Kolmogorov complexity in a broader sense, namely, as the length of the shortest description under some appropriate description mode.

Some of practical computations of language have already been done giving satisfying results and supporting the practice of relating a language to other mathematically graspable complex systems (see Li 1995: 398).

There are, however, many other scientists who have seen language as a matter of mathematics. Probably one of the most important ones is Steven Pinker who states (Pinker 1994: 84) that "language is a *discrete combinatorial system*". It means that it allows unlimited number of completely distinct combinations with an infinite range of properties. According to Pinker, one can ascribe the same characteristics to DNA, the carrier of genetic information. In language, in Pinker's words, "a finite number of discrete elements (in this case, words) are sampled, combined, and permuted to create larger structures (in this case, sentences) with properties that are quite distinct from those of their elements. For example, the meaning of 'man bites dog' is different from the meaning of any of the three words inside it, and different from the meaning of the same words combined in the reverse order."

On the other hand, most of the complicated systems in the world are seen by Pinker as *blending systems*. It means that the properties of the combination lie between the properties of its elements, and at same time the properties of its elements are lost in favour of the originating average or mixture. As an example Pinker offers the situation of mixing red paint with white paint creating pink paint. However, in such systems as life and mind that are open-ended, the situation is different. They are based on discrete combinatorial systems.

Pinker describes the way language works as follows: "each person's brain contains a lexicon of words and the concepts they stand for (a mental dictionary) and a set of rules that combine the words to convey relationships among concepts (a mental grammar)." Each of us is able to formulate an infinite number of different sentences. It means that we are able to make an infinite number of combinations from a finite number of constructive elements, i.e. words. And, Pinker stresses, this capability is the thing that distinguishes the human brain from all artificial devices we know. Grammar is a code that is autonomous from cognition. It specifies how one can combine words to get to a meaning. And this specification is independent of the particular meanings we finally obtain.

What distinguishes people from the rest of the world is their immense freedom – probably the maximum, except for God and other supernatural Powers. Language is no doubt one of the greatest masterpieces of mankind. But, as we saw in the foregoing, it seems that language is something more than only a human product. It is a “living” complex system, satisfying all the criteria of this term and having “life” lying conscious human activity. That is why it is not possible to simulate it using computers; at most we can simulate it to an extent and within a limited time period.

> *‘The name of the song is called “Haddock’s Eyes.”’*
> *‘Oh, that’s the name of the song, is it?’ Alice said, trying to feel interested.*
> *‘No, you don’t understand,’ the King said, looking a little vexed. ‘That’s what the name is* ***called****. The name really* ***is*** *“The Aged Man.”’*
> *‘Then I ought to have said: “That’s what the* ***song*** *is called”?’ Alice corrected herself.*
> *‘No, you oughtn’t: that’s quite another thing! The* ***song*** *is called “Ways and Means”: but that’s only what it’s* ***called****, you know!’*
> *‘Well, what* ***is*** *the song then?’ said Alice who was by this time completely bewildered.*
> ‘I was coming to that,’ the King said. ‘The song really is “A-sitting On A Gate”: and the tune’s my own invention.’[168]

7. Complexity enhancement

In a paper already published in the 19th century C. S. Peirce concluded: “…that there is probably in nature some agency by which the complexity and diversity of things can be increased” (Peirce 1892: 321 and Rescher 1998: 3). He regarded the world’s inexhaustible complexity as connected with nature’s impetus to novelty. He was of the opinion that

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[168] Lewis Carroll [from *Through the Looking Glass*]

evolving natural systems develop new features that require more and more elaborated descriptions. He wrote (Peirce 1935: sect. 6.50 and Rescher 1998: 21):

> But think what an astonishing idea this of *diversification* is! Is there such thing in nature as increase of variety? Were things simpler, was variety less in the original nebula from which the solar system is supposed to have grown that it is now when the land and sea swarms with animals and vegetable forms with their intricate anatomies and still more wonderful economies? It would seem as if there were an increase in variety, would it not?

In other words: in the course of the evolution of the universe, new law-levels emerge that manifest themselves within physics, chemistry, biology, sociology, etc. But, what is the source of this complexity enhancement observed by Peirce? Rescher argues that in nature certain factors (e.g. energy and matter) appear to be self-potentiating. The more of them there is, the more powerful the impetus is towards their production. Such a tendency is seen to result in exponential growth that manifests itself in, for example, the initial phase of a universe – Big Bang – or in the expansion of life through biological evolution in the organic realm.

The same can also be said about complexity, since the operations of a complex system tend, by their very nature, to develop further complexity (see Holland 1995). And this phenomenon is discernible in all fields of complexity studies – in physics as well as the social sciences.

Is the complexity enhancement in nature explicable? Many thinkers have been convinced that it is, and four principal modes of explanation have been proposed: the intelligent design theory, the inherent teleology theory, the chance-plus-perpetuation theory, and the automatic self-potentiation theory, according to (Rescher 1998: 4).

The Intelligent Design Theory represents the attitude of traditional theology, where complexity is the result of the work of intelligence. The world itself is nothing more than a theatrical stage for the activities of such a powerful, intelligent Being that can be called "a creative world-mind" or "world-spirit" or God, for instance. This Being leads the course of all evolution (physical as well as biological) in the direction of increasing functional sophistication. Complexity enhancement is thus impressed upon nature "from above".

One of the most popular contemporary advocates of this idea in the field of biology is Michael J. Behe (Behe 1996). According to him, complexity in nature – and particularly in biology – can only be explained by supposing the operation of an intelligent designer. Behe is a biochemist and thanks to his job he has had a chance to observe the development of this scientific field since fifties. Following his personal experiences he is convinced that the molecular nature of some biological systems –blood coagulation, the immune system, or vision, for instance – is very intricate and that these systems are irreducibly complex.[169] Therefore, those who want to explain such processes with the help of a naturalistic developmental theory (e.g. Darwinian evolution by natural selection) certainly encounters difficulties.

Behe continues that whenever we deal with such interactive systems, we can assume that they are the product of intelligent activity. The reason is that we are not aware of any mechanism, including Darwin's, which produces such operational complexity among collaborative components.

Inherent Teleology Theory sees nature as possessing an intrinsic, self-engendered tendency towards increasing complexity. One of the most dedicated philosophers of this position is C. S. Peirce, already mentioned in the foregoing text. His attitude is best articulated in the following (Peirce 1935: sect. 1.174 accord. Rescher 1998: 5):

> Evolution means nothing but *growth* in the widest sense of that word. Reproduction, of course, is merely one of the incidents of growth. And what is growth? Not mere increase. Spencer says it is the passage from homogeneous to the heterogeneous – or, if we prefer English to Spencerese – *diversification*. That is certainly an important factor of it. Spencer further says that it is a passage from the unorganised to the organised; but that part of the definition is so obscure that I will leave it aside for the present. But think what an astonishing idea this of *diversification* is! Is there such thing in nature as increase of variety? Were things simpler, was variety less in the original nebula from which the solar system is supposed to have grown than it is now when the land and sea swarms with animal and vegetable forms with their intricate anatomies and still more wonderful economies? It would seem as if there were an

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[169] Irreducibly complex means that a system is composed of a number of well-connected and mutually interacting parts that compose the basic functions of this system, while the loss of any of these parts leads to the loss of function of the system.

> increase in variety, would it not? And yet mechanical law, which the scientific infallibilist tells us is the only agency of nature, mechanical law can never produce diversification. That is a mathematical truth – a proposition of analytical mechanics; and anybody can see without any algebraical apparatus that mechanical law out of like antecedence can only produce like consequents. It is the very idea of [mechanical] law. So if observed facts point to real growth, they point to another agency, to a spontaneity for which infallibilism provides no pigeon-hole.

In other words, growth, diversification, and complexification are nothing more than intrinsic developmental tendencies in nature. The physical universe is autoteleological, propelling itself using its own resources into ever grater complexity.

Chance-Plus-Self-Perpetuation Theory, a third major mode of explanation, is composed of two main ideas. The first one says that the merely chance fluctuation of things occasionally brings manifestations of greater complexity, and the second one that complexity, once present, tends to be self-perpetuating. This kind of argument does not need any teleological agent. It rests on a purely naturalistic basis. Ever-increasing complexity is caused by chance events, and then propagated due to complexity's own capacity of enhancement.[170]

The Self-Potentiation Theory is based on the idea that complexity is in its own, inherent nature self-propagating. Similarly, as intelligence, it pushes itself to higher levels through the impetus of its own operation. Complexity is by nature expansive so complexification develops "from the bottom up". But such productivity also goes in the opposite direction, i.e. "from the top down" – it is a two-directional process. It is a kind of a universal phenomenon that more complex systems demand the addition of yet further complexities.[171]

Even though these approaches differ significantly in the way of explanation, their use of the upshot is generally the same. Nature's complexity

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[170] N. Rescher (Rescher 1998: 6) notes to this explanation that there is an obstacle one must face when accepts it and that is the question of whether the actual historical course of complexity-enhancement in nature may not have been too rapid to be explained satisfactorily by the operations of mere chance.

[171] In this context N. Rescher (Ibid.) raises the question of how this phenomenon of complexity-escalation squares with entropy enhancement, as reflected in the second law of thermodynamics. He says that in the final analysis the answer lies in the capacity of simple laws to engender products of great complexity in ways entirely consistent with entropic principles. More on this topic can be found in P. W. Atkins, *The second law*, New York: Scientific American Library 1984.

is still increasing, and behind this fact one can recognize both natural diversity and sc. natural fertility at work. To resolve which approach is the right one is beyond our intentions and abilities. For now we rest with the knowledge that *complexity enhancement is a fact of life in nature* – as Nicholas Rescher stresses. And – as he continues – the question *why* this is so, however interesting and important it may be in the larger scheme of things, can safely remain unresolved. The important thing is that the subject of the emergence of complexity and its survival and propagation are issues of lively investigation in many sectors of contemporary science, ranging from astrophysics to the social sciences (Rescher 1998: 7).

Until now we have been dealing with the increase of sc. *ontological complexity*.[172] However, the increasing *cognitive* complexity of our knowledge is a similarly important issue. According to Rescher, it is even more straightforward. He introduces the following example (Ibid.):

Consider the series:

ababababab…

Suppose that we become able to discriminate two sorts of a's, say *a* and **a**.

The series may then transmute into:

*a*b**a**b*a*b**a**b*a*b…

And suppose that the same thing happens with the b's

*a***ba***ba***b***a***b***ab*…

As we introduce more distinctions, the initial pattern becomes more complex. This is a fact that looks standard: more refined distinctions and difficulties always introduce more intricacy, they work towards greater complexity. It is a well-known fact that the more we know about reality, the greater the complexity we are confronted with.

Our exploration of reality always takes us from the comparatively simple to the comparatively complex. And this brings more and more difficulties into both the process of cognition and dealing with things. Complex statements are harder to understand, complex arguments harder to follow, complex machines harder to operate.

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[172] We introduced this division of complexity in chapter II, 1.

In the *Introduction* at the very beginning of our work we started with the simple statement that “one can find complexity everywhere”. In this chapter we supported this statement with a number of examples. We showed that complex systems exist across almost all scientific fields, beginning with quantum theory, via chemistry, biology, material sciences, computational theory, etc., and including purely human systems as a language, for example. Even though we probably used some arguments that would be hard to accept for some of our readers, or used argument that they may disagree with, one thing is clear: all the systems we introduced are without any doubt complex. But now what? Why did we waste so many pages to support such a trivial fact?

The reason is as follows: the sentence we wrote down few rows ago, “complex systems exist across almost all scientific fields”, can be re-formulated without loosing its meaning into: *The whole world is complex and whatever approach or “filter” we use for observing and studying it we always come across complexity.*[173]

This statement is already not as trivial as the former, since it does not come naturally to us. I am convinced that many quantum physicists, for example, have never used the word ‘complex’ in connection with their work (or very rarely, at best). The situation will probably be similar in the case of chemistry. In contrast, biology and the sciences of man -, linguistics, art, artificial intelligence, etc. – are traditionally the domains where everybody will not only expect the presence of complexity, but are naturally linked with complexity.

Thus, if we continue in this way of thinking we come to the conclusion that, in reality, two competitive approaches to complexity exist in the scientific word. On the one side there is the well established sc. complexity science – pursued at many universities, research centres and labs over the world – and on the other hand there is the fact that complex systems are actually studied almost everywhere without the proper designation. So, what is the role of the former one then? It is difficult to say, since the ‘science of complexity’ has

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[173] Of course, if we manage to avoid excessive reduction. Otherwise we will not encounter any complexity, but only deal with adjusted reality.

never been defined properly. However, if one looks at the research plans and list of publications of people and research group labelled as ‘complexity researchers’, we will find that majority of them deal with problems of artificial intelligence, computational theory, neural sciences and economical or financial modelling. On the other hand, everybody who deals with the problems of language – certainly complex will most probably just call themselves ‘linguists’.

There is nothing wrong with this, but it is a bit misleading. It gives the impression that complexity only means those few things mentioned above and that it is “something special”. However, the opposite is true. Complexity is really everywhere and we should be ready to face it and to deal with it.

The fact that complexity touches almost all scientific domains also has one very positive effect! It offers us a great chance to use many of the *achievements* reached in *different scientific fields* and *to apply them to complexity*. In the foregoing text we already gave a few hints in this direction. Let us remind ourselves of the theory of self-organized criticality, Belousov-Zhabotinsky reaction, Turing’s patterns, for example. And we will mention many others in the next chapter. Although at first glance all of these theories seem completely different and as if they deal with different things, they have something important in common: *their conclusions transcend their original intentions* and *they have become in useful in other branches*; sometimes in very surprising ways. In the case of the purely chemical Belousov-Zhabotinsky reaction, for example, an analogy was found in heart muscle activity.

If we can allow ourselves to anticipate the conclusion of our thesis for a bit, we can suppose that these are all important sources for an *interdisciplinary approach* to the problem of complexity, which we find unavoidable since complexity itself is an ‘interdisciplinary notion’. One can even hope that, from the basis of these conclusions, some “meta-approach” or “meta-language” will rise up that will be useful for dealing more realistically with complexity than has been provided by classical (reductionist) tools of traditional science.

V BREAKING COMPLEXITY

In the foregoing text we tried to answer the questions of what complexity is, how it originates and where it occurs. We came up with quite a lot of information concerning complexity, and we are already more familiar with it. It is no longer a vague term for us, but a clear, accidental category. What remains to be done is some contemplation on knowing and handling it. For, the mere statement that a system is complex - though supported by the knowledge of why and what it means – does not mean much without any further suggestion on how to evaluate it (both qualitatively and quantitatively).

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There are two reasons for searching for methods that allow at least some limited means seizing complexity: on the one hand it is hoped that it would help us to better understand complex systems that surround us – including ourselves – and on the other hand it would provide a possibility that people could construct complex systems – even though probably only the simplest. It has always been a dream of people to play the role of God as creators. In the following paragraphs we will see how much has already been done in this direction.

1. The cognitive aspects of complexity

“All sorts of things can be more or less complex, but the situation is particularly notable with respect to bodies of knowledge” – N. Rescher says in his book *Complexity – A Philosophical Overview* (Rescher 1998: 16). In fact, complexity, like simplicity, pertains in the first instance to cognitive artefacts, such as descriptions, explanations, and accounts, but this is not without its ontological repercussions.

Let us imagine a glass ball-like aquarium with just one fish, one plant and some sand on the bottom. If we ask different people to describe it they will formulate different statements according to their knowledge, interest, personal attitude, etc. A description by a child would certainly be different from that of a biologist – and both would differ from the statement of a person who absolutely does not care for such things as a fish in an aquarium. If we ask for a description in the case of a big aquarium with many fish and plants of different kinds, we will again get different descriptions. Although now none of the people would agree in their statements, whereas in the previous instance they might have had something important in common. They will be significantly longer and more complicated than in the former situation. The conclusion is inevitable: the second system is more complex than the first one.

In the same manner a story considering only one person in one particular situation will be certainly be composed of lesser pages than a novel covering the history of whole families during many decades. In other words: the former is less complex than the latter.

As we can see from the examples stated above, there is a strong link between *cognitive complexity* and *ontological complexity*. The former opens the door to meet the latter. Cognition is an instrument of order-detection, and according to Rescher, this link between complexity and order means that ontological complexity issues an open invitation to cognitive complexity.[174]

Even though our cognitive capacity as humans is significantly limited, cognitive complexity is of particular concern for us. Our scientific efforts to understand the reality of nature are confronted with the challenges of complexity on all fronts. In this context Rescher points out that, due to reality's systemic structure, every field of knowledge is surrounded by others – the history of China stands alongside the history of Japan, the literature of France stands alongside that of the literature of Germany (Rescher 1998: 17).

In nature causal interactions are at work and they make a neat separation in understanding phenomena mostly impracticable. Why did Al-

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[174] We speak about order in connection with complexity, since ontologically complex systems are of a character that cannot be grasped by simple conceptual means.

Qaeda attack New York in September 2001? Who is able to unravel the whole skein of reasons that resulted in this disaster? Despite of the endless number of hypothesis and personal views there is probably nobody who could oversee the situation in its entirety.

But even where there is no *interaction* there is nevertheless *interrelation*. Each phenomenon can be characterised by using comparisons and contrasts. For instance comparative literature, comparative linguistics, and the like, develop via relationships of similarity and contrast a set of issues that simply does not exist alone on either side. And with such high-order studies we always reach new levels of sophistication and complexity in our comprehension of the world's facts, Rescher adds.[175]

Nicholas Rescher further makes distinction between complication and complexity – similar to the way we did at the beginning of this treatise. According to him "'to complicate' as a verb represents a matter of process and procedure generality by treating matters so as to render more complex something that is comparatively less so – introducing an imputed complexity that is actually absent." Thus cognitive incompetence can lead to a perceived complexity that can certainly complicate matters. For example, in the case of perfectly regular sequence of alternating *1*'s a *2*'s if one has difficulty in discriminating between them and frequently mistakes a *1* for *2* (or conversely) one will encounter a sequence that is pervaded by randomness and thus exhibits a great deal of complexity. On the other hand, when the reverse happens and one cannot discriminate 1 from 2 at all, our observer will perceive the random series of 1's and 2's as a uniform series *XXXXXXXX*, which is simplicity itself. However, Rescher stresses, in general *cognitive difficulty reflects* rather than creates *complexity*. "An item's complexity is indicated by the extent to which we encounter difficulty in coming to adequate cognitive terms with it" (Rescher 1998:17).

As we saw in chapter II to distinguish sharply between the category of 'complication' and 'complexity' is quite difficult. Different authors do not agree even on the very fundamental question of this problem, i.e. whether

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[175] The treatment of complex processes through a combinatory fusion of simple ones is the standard cognitive strategy of artificial intelligence research and cognitive heuristics generally. This issue will be discussed later in this chapter.

complication is a field in itself. For instance K. R. Popper writes (Popper 1959: 137):

> To begin with, I shall exclude from our discussion the application of the term 'simplicity' to anything like a presentation or an exposition. It is sometimes said of two expositions of one and the same mathematical proof that the one is simpler or more elegant than the other. This is a distinction, which has little interest from the point of view of the theory of knowledge; it does not fall within the province of logic, but merely indicates a preference of an *aesthetic or pragmatic* character. The situation is similar when people say that one task may be "carried out by simpler means" than another, meaning that it can be done more easily or that, in order to do it, less training or less knowledge is needed. In all such cases the word "simple" can be easily eliminated; its use is extra-logical».

Popper's approach is clearly subjectivist – he sees simplicity (and implicitly complication) as a matter of *mind-projected preferences*. In contrast, Nicholas Rescher argues in his book (Rescher 1998: 18) that "the capacity and the time that a computing machine requires to resolve its problems are perfectly objective matters." Even a cognitively all-powerful God, who has no difficulty whatsoever in managing information, will nevertheless recognize that one subject of understanding is more complex than another or one line of reasoning more intricate than another. Complexity is to all appearances a real and pervasive feature of things.

If complexity does exist – and it does as we saw in chapter II, and as has been supported by the foregoing – it must somehow be measurable and controllable. And this is the topic of the next section.

2. System complexity & observer complexity

> It is conceivable that in some small grain of sand which we can hardly perceive there is hidden a whole world in which there is an immense number of living beings so small that they escape not only our perception, but also the perception of those tiny living beings which we hardly observe under a microscope. Is it not possible that

> there be a long series of such worlds, which, with respect to one another have the same relation as our single grain of sand has to the whole world?[176]

To start this section let me to invite you into our living room. Take a seat and watch the big aquarium standing in front of you. At the first glance you experience a shinning "thing" with something inside. There is some sand, plants, fish, a filter machine, heating, and water, of course. There are many things, but they are still countable and understandable, i.e. simple. If you stay there a bit longer you will start to recognize some order and hierarchy ruling this small, closed system. Sand stays at the bottom because of the law of gravity. Plants grow up toward the light that imitates the natural sunshine. Water flows through the filter machine pushed by the pump using the power of electricity. Fish inhabit the water space each with its own territory. They stay more or less in couples or groups according to the species they belong to.

These are some facts that one can directly and easily observe and just by watching the aquarium. This is the way the aquarium would be described by children, for example. You, as an adult – educated and experienced – would probably be able to "see" much more. You will recognize how the plants grow thanks to the light and food that they both take from the bottom and water. You will notice some of them that are not doing well because they are covered by other floating plants and suffering from lack of light. You probably know that these plants are necessary for fish because they provide the water with oxygen and give them a food supplement as well. You can also see that some fish prefer to stay at the bottom, some of them are stay just below the water surface, some of them stay in groups, others behave like strong individuals. Some of them are dominant – in size and colour – some of them are submissive. At this moment you will definitely change your mind and would not call the system inside our aquarium simple any more. You will be touched by its intricacy and find out that despite its limited size it is pretty complex.

Now, imagine a man standing in the street looking through the window and watching some "shining box". If this man were asked whether he is

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[176] R.J. Boscovich, from his commentary to *Philosophiae recentioribus versibus tradita a Benedicto Stay libri decem*, Vol. III, Romae 1755, pp. 421f; transl.by Milic Capek and Walter Emge.

observing a “complex thing” he would laugh. What would you tell him? “Come inside, please, come closer, watch for a moment and now try to judge!” But, what does this mean? It means that the system’s complexity strongly depends on the observer – on his or her *presence*, *distance* from the system, and even *knowledge*.

> Wheeler … was one of the first prominent physicists to propose that reality might not be wholly physical. In some sense, our cosmos might be a participatory phenomenon, requiring the act of observations – and thus consciousness itself.[177]

However, if this is the case then the system’s complexity is always changed by the act of observation.[178] If there were a wave function – let say Ξ – (analogous to the wave function Ψ in quantum mechanics) bearing all of the information of a given complex system, then every act of observation would change it, analogous to the collapse of the wave function in quantum mechanics. The enormous number of “quantities” (approaching infinity) describing the system’s complexity will “collapse” into the small, countable number that the observer is able to see and understand (depending on his or her distance, pre-knowledge etc., as has been said).

Another problem is that an observer himself is a complex system. This is an inescapable fact bringing forth new questions. Since man is endowed with self-reflection, he can choose between two alternatives at this moment. He can “forget” about his own complexity for the moment and consider himself as an observing and knowing “black box,” or start thinking about how his own complexity may interact with the system’s complexity that is observed. (The second approach probably sounds more attractive, but it would hardly provide us with any real chance to come to some reasonable conclusions; at least not with the present state of knowledge of mankind.[179])

Complexity theory and quantum mechanics share this fundamental problem. Both of them cannot solve it, and yet both of them dream of a *theory*

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[177] “Information, Physics, Quantum: The Search for Links”; in: *Complexity, Entropy, and the Physics of Information*, ed. by W. H. Zurek, Addison-Wesley Reading Mass, 1990.

[178] We suppose that complexity somehow exists even when not observed – as we concluded in chapter II of this treatise.

[179] However, this sc. psycho-physical dualism has found many advocates in quantum mechanics!

without observers, which is necessary for reaching true, objective knowledge of the world.

Similarly to Wheeler, Nicholas Rescher says in his book (Rescher 1995: 165):

> We have no alternative but to act on the basis of what our conscientious cognitive efforts can here and now provide, recognizing that our available information in highly complex matters is all too often less than adequate – and almost never complete. Accordingly, in the informatively difficult and problematic setting of a complex world, reason faces the predicament of acknowledging that it must call on us to do that which, for aught we really know, may in the end prove totally inappropriate.

Besides the problem of “changing” reality by the act of observing or – when formulated from amore realistic point of view – of providing “deformed” descriptions of complex systems due to changing observing distance, i.e. based on different levels of details, we have got ourselves into further trouble. They have been caused by the subjectivist element of “filling in” missing information about reality, according to our own decisions.

In this context Rescher gives the following table of examples different problem-solving situations (Rescher 1995: 166):

Case 1: Informational gap-filling

Data: A manuscript note contains the (partly illegible) passage: “He sent her a l-tter…”

Question: How is that gap in the incomplete word “l-tter” to be filled in?

Case 2: Probabilistic reasoning

Data: 1. X is a mechanical engineer.

2. 90 per cent of mechanical engineers are male.

Question: How probable is it that X is male?

Case 3: Inductive inference

Data: A sequence starts 1, 10, 100.

Question: What are we to expect at the 10th place?

Case 4: Prudential decision

Data: 1. It is starting to rain.
2. Yonder large tree affords the only shelter in the large, flat meadow that we are crossing.
Question: Where should we go?

Case 5: Expert intervention

Data: 1. *X* suffers from asthma.
2. Antihistamines are the most effective available medication for (most cases of) asthma.
Question: What course of action should we recommend to *X*?

In each case, Rescher says, we face a perfectly possible and clearly delineated situation of choice. And in each instance the “rationally appropriate resolution” seems rather obvious and straightforward. But now consider what happens when some additional, supplementary information is added. Let us assume that in these five cases we acquire some further, merely additional information:

Case 1: The passage continues: “to transport her wounded brother”.

Case 2: We are also informed that X gave birth to a bouncing baby boy last week.

Case 3: We are further told that the sequence continues 1, 10, 100, 1, 10, 100, for the next six series.

Case 4: We are given the supplemental datum that there is also much lightning and thunder.

Case 5: We are also informed that X is highly allergic to antihistamines.

From these examples it is evident that the final information-statement will be different according to both the abilities and subjectivity of the person involved and the degree of possible additional information. It means, in Rescher`s words, that in any and every domain, the rational resolution of problems is highly context-sensitive to the information in hand.

3. Could computers overcome our limitations?

Considering the difficulties and limitations that beset our human efforts at problem-solving in a complex word, it becomes tempting to contemplate the possibility that computers might enable us to eliminate our cognitive disabilities. So, can we suppose that there is at least a theoretical chance that computers are cognitively omnipotent? If a problem is qualified as soluble, will computers always be able to solve it for us?

To continue, we must make restrict the problems that we are talking about (according to Rescher 1995: 152). We must definitely leave aside all *practical* problems relating to the management of the affairs of human life, since machines are not (and never will be) the same as humans, and therefore they cannot substitute them in all the richness of their lives. Thus, what we are going to talk about is only the ability of computers to solve *theoretical* problems of the strictly cognitive sort, regarding matters of empirical or formal fact. These problems are accordingly those that characterise the natural sciences, in particular problems relating to the description, explanation, and prediction of the things, events, and processes that constitute the realm of physical reality.

Here one more important thing should be mentioned. When we speak about ‘a computer’ we have in mind more than a mere electronic calculating machine, understood in terms of its operational hardware. We also consider its *software* and its *data acquisition*. Not only can such “computers” *process* information, they can *obtain* it as well. Moreover, the computers we are talking about are also capable of discovering and learning; they are able to significantly extend and elaborate their own, initially programmed, modus operandi. They are actually question-answering devices of a very ambitious order.

When can we indeed consider *a cognitive problem as resolved*? The answer is that *only when an appropriate answer is convincingly provided* – i.e., when we have a solution that we can responsibly accept and acknowledge as such. Moreover, this resolution must be credible and convincing.

When talking about the limits of using problem-solving computers, we should distinguish between *theoretical* and *practical limits*. Apparently there are certain problems that are inherently unsolvable in the logical nature of things. One cannot square a circle. One cannot decide the demonstrably undecidable or prove the demonstrably unprovable. Such tasks represent absolute limitations and their accomplishment is theoretically impossible. It is clear that inherently unsolvable problems cannot be solved by computers either.[180]

Other sorts of problems will not be unsolvable as such but will, nevertheless, demonstrably prove to be computationally intractable. There will always be mathematical questions to which an algorithmic respondent will give the wrong answer, or will be unable to give any answer at all, no matter how much time is allowed.[181] But, this is a mathematical fact and therefore it is of no great interest for us.

What is, however, important for us are problems that computers *cannot* resolve but that other problem solvers conceivably can. Thus, in accordance with Nicholas Rescher, we do not consider theoretical limits in general as meaningful limitations.

When talking about practical limits one can distinguish between the following categories:

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[180] Cf. Kuhn, T. (1962) *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press.
[181] As Turing pointed out in connection with the algorithmic decision theory.

Inadequate information:

Often the information needed for credible problem-resolution is simply unavailable. Thus no problem-solver can at this point in time provide credible answers to questions like “What did Julius Caesar have for breakfast on the fatal Ides of March”, as Rescher stresses (in Ibid.: 155). And he adds the following examples:

Case 1

Data: *X* is confronted with the choice of reading a novel by Dickens or one by Trollope.
And further: *X* is fond of Dickens.
Problem: To predict which novel *X* will read.

Case 2

Data: *Z* has just exactly $10.00.
And further: *Z* promised to repay his neighbour $7.00 today.
Moreover: *Z* is a thoroughly honest individual.
Problem: To predict what *Z* will do with his money.

Although, at the first sight these problems look trivial to solve, it is not necessarily the case. Now, suppose that we acquire some further data:

Case 1: *X* is extremely, nay *inordinately* fond of Trollope.
Case 2: *Z* also promised to repay his other neighbour the $7.00 he borrowed on the same occasion.

As we can see, the body of information that isat hand is not just important for solving the problem, but is *crucial*. And it counts for computers as well as for people. If the available information is not sufficient computers will not be much help to us.

Limits of prediction – real-time processing problems:

The temporal aspect is also very important. Securing and processing information is a time-consuming process and the time at issue can never be reduced to an instantaneous zero. If the solution of a given problem requires data whose determination by observation or measurement involves days, the computer cannot solve the problem in minutes. So, if the problem is predictive, it could find itself in the awkward position that it should have started yesterday on a problem only presented to it today, as Rescher notes. Thus, even with the supposition that the computer can answer *all* of our questions, it cannot, if we are demanding enough, produce those answers whenever we might require them. There will always be problems that are unsolvable “on time”.

Limitations of representation:

It is a matter of a fact that any computer that can be designed and produced is infinite; its sensors are finite, its memory (however large) is finite, and its processing time (however fast) is finite. Moreover, the modus operandi of computers (in software as well as hardware matters) is also based on processes that are digital, discrete, and finite. In particular, all computers operate in the context of finite instructions and finite inputs. Any representational model that functions by means of computers is of finite complexity in this sense. And this array of finitudes means that a computer’s modelling of the real will never capture the inherent ramifications of a natural universe that is infinitely complex in its detail and its machinations. The result is that the inherent make-up of reality exceeds the complexity of detail that computers are able to capture (Rescher 1995: 158).

Nature itself has a complexity that is effectively endless and artifice cannot replicate the complexity of the real. This is a statement with far-reaching consequences. It appears that reality is too complex for adequate cognitive manipulation in general. Our cognitive processing is thus never totally efficient – something is always lost in the process. This is a law of restriction, which unfortunately touches computers as it does every other tool mediating the knowing and modelling of reality.

Self-insight problems

One of the reasons why a computer can never function perfectly is its own predictive performance. This fact is also covered in the sc. *Halting Problem* in algorithmic decision theory. It says that even if a problem is computer solvable – in the sense that a suitable computer will demonstrably be able to find a solution by keeping at it long enough – it will in general be impossible to foretell how long a process of calculation will actually be needed. No computer can provide general insight into how long it – or any other computer – will take to solve problems.

And there are, of course, other questions that a given respondent (human or arbitrary other) could not answer correctly, even though another might have no difficulty with it. For example: “What would be an example of an idea that you never entertain?” or “What will the next unanticipated, predictive question that you will be asked be?”

So, it seems that no computer can be considered to be a universal problem-solver, nor can it possibly provide perfectly correct answers to every meaningful question that can be put to it. And no computer can manage to get a perfect grip on itself. Alan Turing’s dream of a universal computer that can solve all computer-solvable problems is an illusion. For any given computer there will always be some cognitive problems that it cannot satisfactorily resolve (according to Rescher: ibid.).

This discussion is elaborated on in Hubert L. Dreyfus’s book, *What Computers Still Can’t Do*[182] This book –in contrast to our discussion – shows that, beside other issues, there are things that humans can do that computers cannot accomplish. This raises the question if there is a sector of this

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[182] Dreyfus, H. L. (1992) *What Computers Still Can’t Do*, MIT Press.

problem-solving domain where the human mind enjoys a competitive advantage over computers?

It is true that the various computer incapacities to do with description, explanation, and prediction are also mostly things that people cannot do either. Or, in other words, *much of what we would ideally like to do computers cannot do either*. They can indeed diminish but not eliminate our limitations in solving the cognitive problems we confront in dealing with a vastly complex world (Rescher 1995: 163).

4. How to measure or control complexity

In their outstanding book (Coveney 1995), Peter Coveney and Roger Highfield say that, just as no-one can understand any human language without knowing its grammar, *we cannot grasp complexity and deal with it without knowing its own grammatical structure, expressed by the language of mathematics*. Although the word 'complexity' is often used rather vaguely[183] within the domain of mathematics the definition is unambiguous.

In this book the complexity of a problem is defined as the number of mathematical operations needed to solve it. To measure the degree of complexity of the given problem is a task for the mathematical *theory of intricacy*. It evaluates whether the problem is controllable, i.e. whether we should try to solve it. It is very interesting to notice that much of nature's complexity is about solving difficult problems (e. g. how to survive surrounded by predators, or how to adapt to changing living conditions). So, there is doubtless a strong coherence between mathematical and natural complexity.

All mathematically complex systems belong to the category of very difficult problems. This is the reason why they resisted scientific analysis for so long. However, the breakthrough came with the creation of computers and their immense capabilities.

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[183] One example given by the authors is that given by Murray Gell-Mann in 1994: "No definition of complexity is valid by itself. It always depends on context."

To deal with complexity using computers one needs both cleverness and hard work. Intelligence is necessary for exact the mathematical formulation of the problem and hard work is necessary to solve it numerically. Today, complexity science is non-trivially connected with computer techniques and fundamentally depends on it. An enormous increase in computers' operation capabilities during the last fifty odd years has allowed natural scientists and mathematicians to simulate ever more complex phenomena. And what is more, what we experience today is the situation that even super-efficient conventional computers are coming to be considered as anachronisms and are replaced by computers of the new generation, that are closer to real, natural, complex systems, with their ability of evolution and adaptation (though in a limited manner).

Cellular automata

While traditional computers have been constructed to solve problems according to the strictly logical rules of classical mathematics, the trend today is different; people try to get inspiration from nature. This is a very clever decision because the reverse use of computers helps us to better understand nature's behaviour (Coveney 1995: 89).

The first attempt to reproduce the complexity of life was made by John von Neumann who defined life as a 'logical' process in his lecture "General and Logical Theory of Automata", reported at Hixon's symposium in Pasadena in 1948.[184] The desired result was a precise mathematical theory linking together computer complexity and biological systems that process information (as computers do), mainly brains. Von Neumann's aim was to construct a machine complex enough to reproduce. He succeeded to devise a robot – a self-reproducing automaton – floating in a soup of its own components. However, what was probably even more important was his

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[184] Cf. Aspray, W. and Burks, A. eds. (1987) *Papers on John von Neumann on Computers and Computer Theory*, MIT Press, Cambridge, MA p. 391.

pioneering work to unite things, conventionally regarded as incompatible, through logical rules, i.e. nerve tissues and an electronic valve.

After Von Neumann's death, the work was continued by Arthur Burks, who worked as an electrical engineer at the Moore School in Philadelphia. He was also an editor of Von Neumann's posthumous manuscripts on automata theory.[185] Perhaps the most significant, however, was that he was able to attract his student, John Holland, to this research, who was later to build a great career in the subject. In 1960 he proposed an 'iterative circuit computer', a relative of cellular automata, which we shall discuss later on. This computer was already able *to simulate genetic processes* by programs that were able to move, split, associate, rule and construct other programs, and to make its own copies (quoted to Coveney-Higfield's book *Frontiers of Complexity*). A few years later he presented the idea of automata that were even able *to adapt to their environment*. A big step forward was made by Ulam and Schrandt, who showed that simulations of cellular automata can be produced from simple laws, and that huge complex structures that even looked alive could be created.

In 1960's, the game called *Life* designed by John Conway from Cambridge, experienced its boom.[186] The aim of this game was to reproduce the behaviour of real-life systems. The game was equipped with a large chessboard and many flat counters of two colours. The game starts off with only a few squares occupied by counters. The rules themselves are quite simple: If an empty square has three neighbouring squares occupied it acquires a counter, since the cell becomes "alive", nurtured by its neighbours. If a square only has two occupied neighbours, it remains unchanged. Finally, if an occupied square has any other number of occupied neighbours, it loses its counter – the cell dies because of lack of "neighbourly love" or being smothered by overcrowding.[187]

This game showed that complex behaviour could emerge from a simple starting arrangement by applying basic rules to every square. Thus the

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[185] Neumann, J. von (1966) *Theory of Self Reproducing Automata*, A. Burks (ed.), University of Illinois Press, Urbana and London.
[186] Cf. Gardner, M. (1970) SciAm 223**,** p. 120.
[187] Compiled according to (Coveney 1995: 95).

chessboard rules represent the laws of physics (or life) and the patterns signify material objects. Through using computers an endless number of variations of this game exists today. “It has been employed to simulate complex phenomena such as biological development, chemical reactions, crystal growth, the structure of snowflakes, and the meandering of rivers”, Coveney and Higfield indicate. “Cellular automata have been successful at reproducing many aspects of the complexity of the observable worlds such as growth, aggregation, reproduction, competition and evolution”, they continue.

The theory of cellular automata is based on the view that nature is itself *a form of computation*. It means that we treat objects as simple computers, with each obeying its own set of laws. The “cellular automaton” extends this analogy to provide a way of viewing whole populations of interacting “cells”, each of in itself a computer (an automaton). By building appropriate rules into a cellular automaton,[188] we can simulate many kinds of complex behaviour, ranging from the motion of fluids governed by the Navier-Stokes equations, to occurrences of starfish on a coral reef. Thus, cellular automata are used to model “difficult” physical phenomena as for example processes of growth, turbulence in different media, in hydrodynamics, etc. (Green 1993: http.).[189]

It is very interesting and of great importance that one can define uncountable numbers of cellular automaton universes just by choosing different rules that govern their evolution. Now, the question arises whether the behaviour of cellular automata will be equally endlessly variable or if some universal features will emerge. If the later possibility is realised, it enables us to formulate general conclusions about the particular kind of behaviour within *any* kind of complex system simulated in this way!

To solve this problem one must start with the question of how the local rules are related to the resulting global behaviour. According to Stephen Wolfram (Wolfram 1983: 601),[190] regardless of the local rules initially used, one can divide the long-lasting behaviour of cellular automata into four

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[188] Cellular automata are dynamical systems evolving in discrete time according to local deterministic or probability rules. A cellular automaton is an array of identically programmed automata, or “cells”, which interact with one another. The arrays usually form either a 1-dimensional string of cells, a 2-D grid, or a 3-D solid. Most often the cells are arranged as a simple rectangular grid, but other arrangements, such as a honeycomb, are sometimes used (Green, http: 1993).

[189] Cellular automata also have some entirely practical uses, e.g. the study of concrete hardening.

[190] Quoted according to Coveney (1995).

categories: I. patterns[191] disappear and they change to a stable, static and homogenous state; II. patterns have a constant and finite time of duration, and we observe fixed structures that constantly repeat; III. the system only consists of chaotic states; IV. there are irregularly growing and disappearing complex patterns. Then, the "edge of chaos[192] refers to Class IV, because it expresses the dynamical behaviour falling between Class II and Class III.

The evident existence of cellular automata of Class IV has opened the door to a wide range of simulations of real complex systems, especially living ones. It is now possible to transfer some of actual situations (though still only simplified) to a computer and to make a suitable model to predict its future development – for example the response of a chemical system to the addition of some catalyst, or the speed of the migration of an oil slick in soil.

Or, vice versa we can create a system in a computer that could correspond to some similar system existing in the past – e.g. a chain element in the course of evolution – or that could even be found in the contemporary world – e. g. patterns of behaviour within a colony of some unicellular organisms. And it shifts complexity research to new horizons.

Digital evolution

The evolutionary theory of Charles Darwin became so powerful that its influence has also spread to the world of inanimate things. Evolutionary metaphors have also taken root in the computer sciences. Using *genetic algorithms* and *genetic programming* enables people to capture the process of evolution with a computer. "These new methods make it possible, for instance to "breed" a better turbine blade for an aircraft or to find the most efficient pathway for sending information across a vast electronic communication network" (Coveney 1995: 97).

The crucial point of the Darwinian theory is the "survival of the fittest" and closely connected with it is the process of adaptation, an open-ended process by which a structure evolves through interaction with its

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[191] 'Patterns' we understand as manifestations of complexity.
[192] Cf. chapter III, 2 of our treatise.

environment.[193] So, biological evolution is nothing other than an adaptation process expressing enormous complexity. To transfer it to computer means to use the process of optimisation in mathematics.

To make computers – or at least their programs – mimic living things was the main goal of John Holland.[194] He tried to employ adaptive evolution in searching for new solutions for arising new problems. “Since the eighties of the 20th century, genetic algorithms have been used for a broad spectra of problems, from the design of integrated circuits and communication networks, to compiling market portfolios and designing aircraft turbines” (Coveney 1995: 99).

Learning from the environment is of crucial importance for artificial intelligence studies. And, genetic algorithms provide the general theoretical framework for investigating ‘complex adaptive systems’. Holland’s genetic algorithm is easy to construct (according to the ‘principle of survival of the fittest’, employing sexuality and genetic recombination) but is difficult to express in the form of computer programs. Moreover, these computer programs “evolve” analogously to the way indicated by natural selection, and therefore they often solve problems in a manner their own creators themselves do not fully understand.

Neural networks

The first attempt to design a computer based on the structure of the brain was already done during World War II[195] The main idea was quite revolutionary: brain cells, i.e. neurons, can be considered to act as logical switches, operating on the basis of binary arithmetic (Boolean). Thus, artificial neural networks are collections of mathematical models that emulate some of the observed properties of biological nervous systems (cf. Battelle: http.). They are even able to emulate the faculty of living beings to learn adaptively.

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[193] Cf. Chapter III, 1.

[194] Cf. J. Holland, Sci. Am. 267 (1992) 66.

[195] McCulloch, W. S. and Pitts, W. (1943) A Logical Calculus of the Ideas Immanent in Nervous Activity, Bull. Math. *Biophysics* Vol. 5 **,** p. 115.

The basic unit for information processing within the nervous system is called a neuron. The neural network consists of a large number of interconnected neurons. It is a completely natural thing, created by the “Mother Nature”. Neural nets are connected to terminations of nerves that represent “data busses” for an organism. Then, the task of neural nets is the back drive of organism behaviour. Neural nets are composed of individual neurons and each of these neurons has many inputs, but only one output. Inputs are called dendrites and they are connected to outputs (axons) of other neurons. One neuron in the human brain is connected to approximately 10 000 – 100 000 other neurons. When some of these neurons supplying information are removed, nothing serious happens. The resulting behaviour of the whole neural net will stay unchanged.

Neural nets are able to learn and, thanks to this ability animate organisms behave adaptively. Learning means to draw conclusions from experience. Adaptability to the environment through such mechanisms is called *intelligence*.

Artificial neural networks (ANNs) were originally developed as tools for the exploration and reproduction of processes involving information processing made by a human brain. Such processes are: speech, vision, touch, olfaction, hearing, processing knowledge, motor control etc. At present the field of interest has shifted. Most research is now directed towards the development of ANNs for applications such as data compression, optimisation, system modelling and control.

Learning is based on the adjustments of the synaptic connections between neurons. The same principle applies to ANNs. Learning occurs through training, where the system being “educated” is either given the right examples, or is exposed to a set of input/output data, where the training algorithm iteratively adjusts the connection weights (synapses). These connection weights store the knowledge necessary to solve specific problems.

There are many examples of practical uses for neural nets, because their applicability is very wide. Coveney and Highfield give the setting of cement slurry as an example (Coveney 1995: 147). Let’s consider the infrared spectrum of slurry as being the input for the modelling process. The ingoing layer of the net receives information – for a period of time – about the correlation between the absorption of infrared light upon different wavelength and the setting of cement. During this period the net “learns” about this correlation and creates the setting-curve for one particular IR spectrum. Then, the net receives a new spectrum, and its task is to choose the right answer to the question of the course of cement’s setting. The net still has the possibility finding the correct answer and “improving its knowledge”. In the next step, the correct answer is completely unknown to the net, and its task is to make a prediction. Finally, such an educated net is able to predict the course of the setting of cement by virtue of only the knowledge of the connection between IR spectra and the changing composition of the slurry during its setting. And this is more than any man or conventional computer could do.

The main difference between computers and artificial neural networks consists in following: Conventional computers rely on programs that solve problems using a pre-determined series of steps – algorithms. These programs are controlled by a single, complex central processing unit and the information is stored at specific locations in their memory. On the other hand, AANs use highly distributed representations and transformations that operate in parallel. They show distributed control over many highly interconnected neurons and store their information in variable strength connections called synapses (Accurate: http.).

Artificial Intelligence

“It is not my aim to surprise or shock you – but the simplest way I can summarize is to say that there are now in the world machines that can think, that can learn and that can create. Moreover, their ability to do these things is going to increase rapidly until – in a visible future – the range of problems they can handle will be coextensive with the range to which the human mind has been applied.”

Herbert Simon

Artificial Intelligence (AI) is an area of computer science focusing on creating machines that can imitate human-like behaviour. To create intelligent machines has been a human dream since ancient times. Today, with possessing the hi-tech computers and 50 years of research into AI programming techniques, the dream of smart machines is becoming a reality.

Researchers are creating systems that can mimic human thought, understand speech, beat the best human chess player, and countless other feats never before possible.

In the words 'artificial intelligence' the former is well understandable while the later is quite tricky. How should we understand the term 'intelligence' in this context? John McCarthy from the Stanford University (McCarthy: http.) defines it as "the computational part of the ability to achieve goals in the world. Varying kinds and degrees of intelligence occur in people, many animals and some machines." In fact, there is no solid definition of intelligence. It is always somehow related to human intelligence. AI scientists are not even consistent in their opinion of what kinds of computational procedures should be called 'intelligent'. Moreover, intelligence involves mechanisms that only some computers are able to carry, but not others. So, their skills are rather limited, but still "somewhat intelligent", McCarthy continues.

AI research started after World War II when a number of people independently started to work on intelligent machines. But Alan Turing is considered to be the founder of this scientific field, and particularly because of the lecture he gave on it in 1947.[196] However, already in the 1930s Turing and Kurt Gödel showed that the practical construction of such a kind of machine is a non-trivial task. The main problem consists in the fact that computer intelligence is based mainly on solving mathematical algorithms. But, these two mathematical logicians succeeded to show that algorithms that were guaranteed to solve all problems in certain important mathematical domains *did not* exist.[197] And, people do it all the time… This is an argument often used against AI that computers are from principle incapable of doing what people do familiarly.

The first work demonstrating the possibility of artificial life was performed John von Neumann in the late 1940s (Coveney 1995: 237). He created so-called kinematic model with the ambition to separate the logical

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[196] The reader can find a nice overview of the history of AI research in Coveney-Higfield's book "Frontiers of Complexity" (Coveney 1995).

[197] Therefore, computability theory and computability complexity cannot address the fundamental problems of AI although they are highly relevant to them (McCarthy: http.).

content from the process of biological self-replication. Von Neumann came up with his self-replicating automaton a few years before the discovery of the structure of the genetic blueprint (DNA)! Since that time many researchers have tried to realize his ideas and at present these efforts are even stronger, because contemporary modern computers are able to deal with more complexity.

So, is it possible to imitate Darwinian evolution inside a computer? Doubtlessly it is, yet here is one big difference between the principle of life on Earth and that inside a computer: Life on Earth is restricted to carbon-based organisms, while “life” inside the computer must be based on logical instructions. However, evolving machine-codes should be able to generate any amount of complexity, so computer-based evolution should have the same (or at least comparable) potential for developing complexity (i.e. life) biology.

When speaking of artificial life we can distinguish between two forms: *weak* and *strong artificial life*. These two rather philosophical positions correspond to two uses of the term ‘artificial’ itself. One meaning of this word is that the thing being referred to is fake, i.e. an imitation of something else (e.g. artificial flowers). The second meaning, on the other hand, suggests that the process by which the referent was produced is man-made or unnatural in some sense, but that the thing itself is just as real as the original (e.g. artificial light).

Analogically, Weak Artificial Life (WAI) can be regarded as an attempt to learn more about biological life (or to create artefacts such as robots) by creating synthetic models of various processes associated with living organisms (e.g. evolution) on computers and other artificial media, but it does not claim that any parts of their models are actually living themselves. On the other hand, proponents of Strong Artificial Life (SAI) believe that by instantiating such processes in artificial media, the end product will be just as deserving of the term ‘living’ as are biological organisms. In other words: WAI is about *simulations* of life while SAI is about its *realisations.*[198]

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[198] According to Timothy Taylor’s Ph.D. thesis, University of Edinburgh (1999);

The applications of AI are many. Probably the most common nowadays is game-playing. There are machines commercially available that can play master level chess, and when they play against most people they are very successful, mainly through brute force computation. There is some AI in them but not enough to beat a world champion for example.

People try to teach computers to understand natural language. Currently they are able to create sequences of words and to do parsing of sentences. However, to really understand what is that the text is about is presently only possible for very limited text domains.

Another difficult problem for the computer is three-dimensional vision. Computers' TV cameras as well as the human eye receive two-dimensional signals from the surrounding world. However people are endowed with three-dimensional vision and work with information that is more than just a set of two-dimensional views. Currently computers only have limited possibilities to present three-dimensional information directly, and their abilities still lag far behind those of human beings.

Since the middle 1970's there have been many attempts to design a sc. expert system, which would be specialized on a certain domain and carry out tasks within it. Achievements in this attempt have not been many. One of the most successful ones was designed for banking purposes, namely a system for advising whether to accept a proposed credit card purchases. A computer has information about the owner of the credit card, his record of payment, about the item he or she is buying, and about the establishment from which he is buying. It evaluates all this information and makes a decision – if it were done by a man it would occupy him for much longer time (according to McCarthy: http.).

In 1959 one of the most famous Artificial Intelligence laboratories was founded at MIT. Since then most of the AI research in the world has been done there. Their characteristics and motivation is nicely expressed in the foreword of their web site. "Our goal is to understand the nature of intelligence

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cf. Pattee, H.H. (1988) *Simulations, realizations, and theories of life*, In C. Langton, editor. *Artificial Life*, vol. VI of Santa *Fe Institute Studies in the Sciences of Complexity*, pages 63-77, Reading, MA Addison-Wesley. Reprinted in (1996) The Philosophy of Artificial Life', M. A. Boden (ed.), Oxford University Press.

and to engineer systems that exhibit intelligence. We are an interdisciplinary laboratory of over 200 people that spans several academic departments and has active projects ongoing with members of every academic school at MIT. Our intellectual goal is to understand how the human mind works. We believe that *vision, robotics, and language are the keys to understanding intelligence*, and as such our laboratory is much more heavily biased in these directions than many other Artificial Intelligence laboratories."[199]

Though the history of the MIT AI lab is quite a long one its greatest achievements have come within the last two decades, hand-in-hand with progress in computer technologies. Over the last fifteen years they have succeeded in building artificial insect-like creatures, with their own specific behaviour[200] and recently they have even built human-like robots with which they can have social interactions similar to that of humans[201]. Nevertheless, these systems are still only machines, and they are not alive. There still seems to be *something missing* (Brooks: http.).

On the other hand, Rodney Brooks says, scientists are quite successful at modelling various physical systems. But what we still cannot do is to model living systems, whether small or large. Perhaps we are missing something fundamental and currently unimagined that prevents us from reaching our desired goal. The question now is: What is the nature of this missing element? According to Brooks, one future possibility is that we will discover some aspect of living systems that is invisible to us right now. He proposes (Brooks: http.):

> One might imagine that there is something on a par with the discovery a century ago of radiation, which ultimately led to our still evolving understanding of quantum mechanics… Some such discovery might rock our understanding of the basis of living systems, and indeed there could be different such discoveries for various aspects of living systems, such as evolution, perception, etc.

Another possibility is that what is missing is not any "unknown physics" in living systems, but only some "new mathematics". It might turn out that we are simply not seeing some fundamental description of what is going on in

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[199] http://www.ai.mit.edu

[200] Cf. Brooks, R. (1999) *Cambrian Intelligence*. Cambridge, Massachusetts.

[201] Cf. Breazeal, C. (2001) *Designing Sociable Robots*. Cambridge, Massachusetts.

living systems.[202] These are issues that are currently preoccupying the scientific world.

5. Unified theory of complexity

We called this section “the Unified theory of complexity”, however, as we saw in the foregoing, ‘complexity’ is a term applicable to all parts of the world. There is no area in the universe where we could say: “Here complexity never occurs”. All natural systems that are left in their natural contexts can be considered as complex. Thus our “unified theory of complexity” overlaps to some extent with “the Theory of Everything” – the dream of the natural sciences – and “the Final Theory” of Steven Weinberg.

According to R. B. Laughin and David Pines (Laughin 2000: 21):

> The Theory of Everything is a term for the ultimate theory of the universe – a set of equations capable of describing all phenomena that have been observed, or that will ever be observed[203]

The effort to discover such a theory is nothing new. One could already find first attempts in ancient Greece, in Milet, one century before Socrates was born. Thinkers from Milet tried to explain all natural phenomena on the basis of the fundamental parts of a matter. Regardless of what they considered these parts to be (air, fire, water or *apeiron*) it represented a kind of reductionist ideal that is re-born in “the Theory of Everything” and its “relatives”.

While “the Theory of Everything” is a term known from physics and almost all views connected with this theory stay within the frame of physics, our “Unified Theory” can be comprehended more broadly, because complexity does not only touch other scientific disciplines (e.g. biology, information science or linguistic) but also psychology and the field of human spirituality. However, historically the search for a final theory usually limited itself to the

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[202] Cf. Brooks, R. (2001) The relationship between matter anmd life, Nature, No. 409, p. 409.

[203] Cf. G. R. Gribbin, *The Search for Superstrings, Symmetry, and the Theory of Everything*, Little Brown, New York 1999.

natural sciences – to physics in particular, which is considered as a basis for the others, that are to some extent drawn from it – and only very few "raving enthusiasts" have ever tried to cross these borders.[204]

The modern history of the hope for a final theory is connected with the name of Isaac Newton, who was first able to explain a wide class of phenomena on the basis of the laws of motion and gravitation – from the famous fall of an apple from a tree, via tides, to the motion of planets and moons. It brought him the belief that all natural phenomena could be explained by the same forces as those mechanical ones mentioned above; he stated in straight words in his *Principia*. Although the future progress in physics, chemistry etc. showed that the situation is much more difficult than Newton had guessed, at the end of 19th century many scientists believed that physics was almost finished and the current theory was viewed as satisfying.[205] But the 19th century had not finished with physics and the certainty of people's understanding of the world fell down like house made of cards.

In 1885 Wilhelm Röntgen found a new radiation called *X*, and later Röntgen radiation was named after him. This discovery had a fundamental impact on the whole of science. Not only because of the importance of X-rays themselves, but mainly because it proved that there were many things yet undiscovered, and that physics was actually far from being finished, as had been supposed. After that discovery new disclosures followed one another in quick succession. The time of surprise and the loss of certainty was not to last long. The former belief in Newton's physics was soon to be replaced with the belief in a new theory, capable to unify at least whole directions in physics – a theory based on atoms and atomic forces.

Although this idea had only a vague shape at this time, it started to come true in the middle of 1920's when quantum mechanics was founded. Already in 1929 Paul Dirac, one of the founders of quantum mechanics, stated in triumph that "the fundamental physical laws – the basis of the

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[204] One of them is F. Capra with his book *The Tao of Physics*, Bantam Books, London 1984.

[205] One should stress at this point that the physical theory current at the end of 19th Century was purely reductionistic and mechanistic. But the world was regarded in the same manner, i.e. quite simple (at the most complicated) and mechanistic.

mathematical theory of the most of physics and all of chemistry – are completely known. The only difficulty consists in the fact that application of these laws leads to equations that are too difficult to be solved."[206] However, what used to be a big problem in the past, is nowadays a matter of routine. We know how to solve the Dirac (or Schroedinger) equation for physical and chemical problems, even when it involves many particles. Almost all believers in a final theory agree that whatever form it takes, it will still be a quantum theory. S. Weinberg says: "I think we'll be stuck with quantum mechanics".[207]

Quantum mechanics was not the only candidate to play a role in creating a final theory. Similarly powerful candidate was also Einstein's general theory of relativity, and recently also the mystical theory of superstrings, linking both these theories together. Whether these theories will be confirmed as parts of the desired final theory or not we shall see in future. It may also happen that this competition will be won by a completely new, as yet unknown, theory. Nevertheless, we can suppose that if the theory is "Final" it will probably be rigid, i.e. stable against modification into another theory, without creating logical absurdities – as Steven Weinberg said in his *Dreams of a Final Theory* (Weinberg 1993).

Weinberg, for his part, strongly believes in the possible existence of a Final Theory, and he is often criticised for this opinion. He comments on this in the same book as follows: "If one starts to speak about a Final Theory some philosophers and scientists start to argue immediately." One is blamed for being a reductionist, or even for claiming physical imperialism. This can be caused partly by the fact that people sometimes see the Final Theory as identical to nonsense, for example that final physical theory means the end of science.[208] According to Weinberg this will not be the case. Such a theory would mean the end in only one sense: it would be the end of many centuries of effort to find the principles that *cannot* be derived from other, deeper principles.

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[206] Dirac, P. A. M. (1929) Quantum mechanics of Many Electron Systems, Proceed. Royal. Soc. A 123, p. 3.

[207] An interview with S. Weinberg, In: Horgan, J. (1996) The End of Science, Facing the Limits of Knowledge in *The Twilight of the Scientific Age*. Addison-Wesley Publ. Comp.

[208] This is also the title of the famous book by J. Horgan (1996).

One of the opponents of the Final Theory is the famous modern philosopher Karl Popper. He actually denies “the idea of a final explanation” at all (Popper 1972: 195). According to him “every explanation can be further explained with the help of some more universal theory, or by an assumption. No explanation can exist that would not need any further explanation…” However, it is rather difficult to imagine the consequence of still more and more fundamental theories – as Weinberg observes – that would not converge somewhere. It is possible, but not probable – he continues – that it will neither continue ad infinitum, nor reach any end. According to Michael Redhead – a philosopher from Cambridge – the chain of such theories could return into its starting point[209] As an example he proposes the orthodox interpretation of quantum mechanics that requires the existence of macroscopic observers and measurement devices, which are inversely explained by quantum mechanics.

John Wheeler, who claims that no fundamental law exists, and that all the laws that we study at present are imposed onto nature by us through the way that we carry out our observations, advocates an even more radical opinion.[210] Even though this possibility is alarming, there is one somehow even worse possibility. Maybe the Final Theory exists as a simple set of principles that are the basis for all explanations, but that we will never be able to know what it is…

Up to now we have only let physicists and philosophers speak, and concentrated on physics. But, as we pointed out at the beginning of this section, the sense of the term “complexity” goes far beyond physics. It touches everything. However, this statement cannot be considered as simple and without the need for further explanation. Why? P. W. Anderson, when he worked on this problem, used a nice bon mot: “the Theory of Everything is not a theory of every thing” (Anderson 1972: 393).[211] Even if we knew all of the theories of all the individual systems that exist in the world and we made a sum of these theories, it would say almost nothing about the world as a whole.

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[209] Cf. Redhead, M. (1989) *Explanation*).

[210] This possibility is elaborated on in Davies, P. (1988) What Are the Laws of Nature, in: *The Reality Club No. 2* (J. Brockman ed.), New York: Lynx Communications.

[211] See also (Laughin 2000: 28).

On the other hand, “the Theory of everything” – if it existed – would probably not contain information about all the single systems that the world is composed of. The reason is simple: “more is different” – as P. W. Anderson’s famous statement has it.

6. Quantum mechanics outside its borders

In classical physics both the measurement device and the measured object are described in the same “language”. The language of quantum mechanics, however, differs significantly from the language of “ordinary experience”, i.e. language expressing classical results.[212] This is the reason why the notion of measurement has been at the centre of scientist’s attention since the very beginning. Numerous discussions have resulted in the formulation of the postulate of the *collapse* or *reduction of the wave function*, which was first explicitly formulated by J. von Neumann in his famous textbook from 1932 (Neumann 1932). According to von Neumann, every process of measurement done on the quantum system contains some “unidentifiable element” that causes the quantum system to undergo “non-continuous, non-causal and sudden” change in the moment of measurement.

Let us imagine an experiment where we try to find if the energy of a particle lies within a certain interval of values. According to the orthodox interpretation of quantum mechanics, we cannot get the answer before the measurement; we cannot even say anything about it. All of the information about the system is contained in the total probability that is equal to the sum of the squares of two individual amplitudes ψ_{yes} and ψ_{no}: $|\Psi|^2 = |\psi_{yes}|^2 + |\psi_{no}|^2$. At the moment of measurement, however, a “jump” to only one possibility happens and $\Psi = \psi_{yes}$ or $\Psi = \psi_{no}$. Which of these two possibilities is realised is said to be completely arbitrary.

The important question now is what the mechanism is for the realising of these “jumps” and also whether they *really* happen. Or is it only our lack of knowledge that distorts our view of atomic events? Up to now many theories

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[212] We refer to the foregoing text where Born’s probabilistic interpretation of quantum mechanics was mentioned.

have been formulated to solve this problem. To give an overview of all of them, however, would require a whole separate treatise.

The important point here is the fact that orthodox interpretation *de facto* divide the physical world into two parts: "classical" and "quantum". Since quantum theory itself does not give any satisfying instruction on how to make this cut, this part of the theory is now mainly considered to be artificial, unreliable and thus temporary.

One of the interesting answers to the question of the existence of the "classical domain" is proposed by the theory of *decoherence*[213], formulated by W. Zurek at al. (Zurek 1981, 1982) at the beginning of 1980's. This theory tries to show how classical reality "emerges" from the substrate of quantum physics (Zurek 1991). In other words, why we do not see quantum superpositions in the world around us (Tegmark 2001: http.).

According to this theory coherent quantum superpositions persist only as long as they remain hidden for the rest of the world. Moreover, decoherence calculations show that a human observer is not necessary to get this effect – even an air molecule is sufficient. Thus, we do not see the quantum superpositions because quantum mechanics would stop working for "big" objects, but because such objects are almost impossible to keep isolated to the extent needed to prevent decoherence. Microscopic objects, on the other hand, are more easily isolated from their surroundings and therefore they can keep and show their quantum behaviour.

The mathematics of the theory of decoherence is quite difficult, and for the moment the verbalized idea is the only thing that interests us. Nevertheless, we should add that in the mathematics also faint light of theory lies. To define the parameters of the environment that are able to reduce the number of observed states of the system, one should divide them into two groups: sc. relevant and irrelevant degrees of freedom. Only the later group is able to interact with the observed object and to "make" a classical thing from it. So, this idea still needs to take account of an observer and his/her/its faculties still matters.

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[213] This effect was named *decoherence*, because an ideal pristine superposition is said to be coherent (Tegmark 2001: http.)

Many Worlds Theory (MWT)

> *"I tend to think these are just puzzles in the way we talk about quantum mechanics… One way to eliminate these puzzles would be to adopt the many-worlds interpretation of quantum mechanics… There may be another parallel time track where John Wilkes Booth missed Lincoln and… I sort of hope that whole problem will go away, but it may not. That may be just the way the world is."*
>
> *Steve Weinberg*

In 1957 H. Everett III (Everett 1957: 454) proposed the monistic interpretation of quantum mechanics that does not require – in contrast to the orthodox interpretation of quantum mechanics – any additional dynamic postulates describing the process of measurement. In literature it is often called "many worlds interpretation" or "many worlds theory".[214] Everett's intention was to formulate quantum mechanics in such a way that it would be suitable for the time-space geometry of the universe as a whole; in other words, a description of the system, where neither classical observer nor measurement device staying outside plays any role.

For explaining the basis of the theory we shall use the following simple example (cf. Penrose 1994). Let us consider a system composed of a detector and a photon, where the photon is in some state of superposition[215] on the two photon's states I and II. Then consider that the detector can be activated only by a photon in state I and never by a photon in state II. (States I and II can represent photons moving in opposite directions, for instance.) According to Everett, the can detector also be described in the language of quantum mechanics and thus find itself in some quantum state. When the detector interacts with photon I, the state of detector changes and photon "disappears".

Now imagine that the detector is observed by an observer. In Everett's theory an observer is considered to be a "pure physical system" that can be

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[214] However, in the original paper (Everett's Ph.D. thesis) we would not find this name.

[215] The principle of superposition is one of the fundamental laws of quantum mechanics and it is completely "non-classical", i.e. it does not exist within classical physics. According to this principle, any complex linear combination of arbitrary state vectors (each state vector represents one of the possible states of the system) also represents some possible state of the system.

described within the theory. So, we can assume that the "state of an observer" is also represented by the quantum state vector.[216] The observer watches the detector and he either sees that the photon impacted it, or that it didn't. In both of these situations the original state of the observer is changed, but in each situation in a different manner.

So, the resulting state can be understood as the superposition of two alternatives: in each of them the state of the observer is connected with to the corresponding states of the detector and the photon field. The first "branch" of this superposition describes a state where photon is absorbed, the detector detects it and the observer observes it. The second "branch" corresponds to a similar situation, but where the photon has not been absorbed.

Everett calls these co-existing states of the observer *relative*, and calls his own formulation of quantum theory the "formulation of relative states". According to this theory, the relative states of the observer create – symbolically speaking – different "copies" of the observer's "self" or different alternatives of viewing the "world", while each of these "copies" corresponds with its own observing.

Everett's paper deals mainly with the description of successions of measurements and the branching of the observer into relative states, corresponding to different results recorded in memory. The mind of every man is thus considered to be "branched out", and as still branching when observing. Each "part" of his or her mind has different classical – not-quantum – experience. And it is these "experiences", expressed here by the relative states of the observer's memory, which defines different "worlds" of Everett's interpretation.

The breakthrough moment of MWT was the idea that the world does not have to be divided into classical and quantum parts. The laws of quantum mechanics are considered as fundamental and they are valid in the macroscopic world as well. Due to "shifting" both the observer and the measuring device to the quantum level, there is no more need to speak of the quantum paradox of the wave-pocket collapse [217], and both the observer and

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[216] Everett actually speaks of the possibility of a quantum description of the state of *memory* of the observer.

[217] This was mentioned at the beginning of this section.

the device loose the key role they played in “creating reality” when choosing only one reality from all the alternatives. All of these alternatives are now considered to be identically “good” and all of them are realise. The problem is how it is possible that we only experience one of them in each moment. Why are we not aware of all the branches of our mind (“self”)? What is the criterion according to which the world as the one we are living in?

Though these objections are rather “philosophical”, there are also some purely physical ones. The point lies in the fact that within the frame of this theory, no satisfying definition exists of “how” the observer, together with the world, should branch (when we put it into ordinary language). Why should the observer from our example not be “sensitive” to other states of the detector, then registering or not registering the photon? Why is this “perceiving-being” not able to perceive the linear superposition of golf balls, or elephants, at completely different places? (Penrose 1994).

Quantum histories (QH)[218]

Von Neumann recognised long ago that the properties of a physical system can be expressed by stating that the value of some observable *A* lies in some range Δ at a definite time *t*. He also showed that such a property is associated in a unique way with a definite projection operator *E* in Hilbert space[219], depending upon *A* and Δ, the dependence upon *t* following from Schrödinger’s equation[220] (Omnès 1995: 725).

We usually encounter the expression ‘history of a system’ when talking about various properties occurring at different times and resulting in a *history*

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[218] Here we apologise to our readers, for the following section will be more technical than the others within this work. We venture this since we need a detailed analysis of this issue for the very end of the work where we will try to apply this theory to a general complex system.

[219] Hilbert space $\mathcal{H}$ is a complex vector space where the scalar product is defined and it is consistent. In the framework of quantum mechanics every state of the given physical system is represented by a vector within the Hilbert space $\mathcal{H}$ that is adjoined to this system.

[220] Neumann J. von (1932) *Mathematische Grundlagen der Quantenmechanik*, Springer Berlin.

of a system. Consider the following example: a neutron enters a monocrystal at some time, after crossing a window in a shielding, its velocity was in a definite range (a property of velocity); the neutron enters a hydrogen target (a property of position); a reaction $n + p \rightarrow d + \gamma$ takes place; soon afterward the photon enters a detector (again a position property). This is what Griffiths called a history: a series of properties occurring at various times.[221] It violates Bohr’s injunctions not to speak about a microscopic object, but everybody does it and it works, as Omnès objects.

Quantum history is a sequence of successive observations. However, since we want to keep a realistic point of view, we will speak of *the succession of values of the certain characteristics of the quantum system that were realised in certain time instants*.

We can consider another example of a particle that finds itself at the time instant **t_1** in the space interval **x_1**, at the time instant **t_2** in the space interval **x_2** … **(t_n, x_n)**. This is history **H**. Then imagine another history **H’** which would consist of the same time sequence, but different space intervals: **(t_1, x_1')** … **(t_n, x_n')**. Both these histories in fact represent two different “trajectories” of the particle.

In the same way we can create histories where, instead of coordinates, momentum is considered. Thus the histories are now as following: **(t_1, p_1)** … **(t_n, p_n)** and **(t_1, p_1')** … **(t_n, p_n')**.

These histories represent different “trajectories” in momentum space. Moreover, these trajectories can even be interfused and one can still speak of histories (even though these trajectories are not simple). For instance: **H’**: **(t_1, x_1) (t_2, p_2) (t_3, x_3)** … **(t_n, p_n)** and **H’**: **(t_1, x_1') (t_2, p_2') (t_3, x_3')** … **(t_n, p_n')**.

According to quantum mechanics, when one knows the initial or terminal state of a system then it is possible to count the probability of each such history. In other words: when, for example, the initial state of a certain system is known, then all its histories have their own probabilities.

Now let us consider the famous two-slit experiment: at the beginning **(t_1)** particle is in a certain state of momentum, at the time instant **(t_2)** it goes through the split and at the moment **(t_3)** it pitches on the screen. If we mark its

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[221] Griffiths R. (1994) J. Stat. Phys., Vol. 36**,** p**.** 893.

passing through the slit 1 as $\mathbf{x_2}$, through the slit 2 as $\mathbf{x_2'}$ and through both slits $\mathbf{x_2''}$ – the screen is $\mathbf{x_3}$ – we obtain the set of histories as following:

$\mathbf{H: (t_1, p_1)(t_2, x_2)(t_3, x_3)}$

$\mathbf{H': (t_1, p_1)(t_2, x_2')(t_3, x_3)}$

$\mathbf{H'': (t_1, p_1)(t_2, x_2'')(t_3, x_3)}$.

In history **H** the particle went through slit 1 and impacted on the screen. In history **H'** it "chose" slit 2 and then impacted on the screen. In history **H''** it went through slit 1 *or* slit 2 and impacted on the screen. However, under the ordinary conditions $\mathbf{P(H'') \neq P(H') + P(H)}$. This is called *interference*.

When we place some "microdetector" behind the slits which interacts with the particle in such a way that its resulting state detects what slit the particle went through – the initial state of the microdetector is also important – then we get the familiar relation $\mathbf{P(H'') = P(H') + P(H)}$. By changing the dynamical conditions this set of histories also changes and the interference has disappeared.

Another effect should also be mentioned here – sc. *decoherence*. A macroscopic object involves two kinds of variables: collective objects and microscopic objects that describe the matter of the object (the electrons in it, for instance) and its immediate surroundings (atmospheric molecules, for instance). A theoretician describes these as two abstract dynamical systems, a collective one and a sc. "environment" that has a very high degree of freedom. The two systems are coupled, and energy can be exchanged between them, resulting in dissipation.

The whole system has a density operator ρ. If only the collective properties are to be considered, all information about them is contained in a simpler, so-called reduced density operator ρ_r, which one obtains – roughly speaking – by ignoring the environment. The decoherence effect comes in here: some collective observables exist, most often at position coordinates *q*, for which every possibility of observing quantum interferences between macroscopically different states vanishes.

This effect has the same origin as dissipation, namely the coupling between the collective system and the environment. The only physical system one may expect to eventually show macroscopic interferences or other purely quantum effects must therefore be non-dissipative.

It is believed that if we put together both these theories – consistent histories and decoherence – the existence of decoherent histories enables us to grasp the classical or at least quasi-classical behaviour of macroscopical systems, which is not possible within classical quantum mechanics. And this is the biggest advantage of this "new interpretation"; it does not force us to divide the world we live in into two separate domains, the quantum and the classical.

One might say that the universe found itself at some initial state that it is possible to define. Thus, if one were clever enough, one could write the whole set of consistent histories of the universe. And these histories would represent the different alternatives that are classically observable. Although in reality I can observe only *one* of them, it does not matter; the other can be realised somewhere in other universes, for instance. But, there is an infinite number of such sets of consistent histories! Which one is the right one? This is a problem that the theory cannot solve yet.

R. Omnès proposes that the only exit from this problem consists in the following (Omnès 1995: 727):

> Every description of a physical system should consist of histories belonging to a unique consistent family and every reasoning should consist of legitimate implications.

The biggest success of this theory consists in the fact that it enables us to reproduce all the results of "ordinary" quantum mechanics and furthermore – under particular conditions – to go from the purely quantum description to a sc. quasi-classical domain, where ordinary language and logic work again.

According to this theory an infinite number of alternative histories exist, and all of them are equal in the same manner as the worlds within Everett`s MWT. However the world we experience is only one. According to Omnès it could be right at the moment where we collide with a border of the use of physics and maybe even science as a whole. For physics, all predicted individual alternatives will probably stay "equally real" forever, and *how* "true reality" emerges from these potentialities may remain a secret beyond its competence.

Quantum physics and conscious thought are many-world points of view: Here one is allowed a form of 'strong determinism, without determinism'. The totality of all possible universes may be thought of as a single structure – the *omnium* – and one might take the view that it is the omnium that is completely fixed by mathematical rules. Possibilities (or randomness) now arise owing to the uncertainties involved in the question of where one finds oneself located within the omnium. This 'location' involves not only one's spatio-temporal location within a particular universe branch, but also the selection of that particular branch itself.[222]

Quantum mechanics and the theory of complexity have much in common. They deal with systems that are difficult to grasp rigorously for many reasons. These systems are too small, too big, too far, too deeply connected with other systems; they are multi-layered and bonded in non-trivial relations; they are only partially visible and knowable depending on the observer's pre-knowledge etc. Both these theories search for their own solutions of their own problems, however, it may be the case that it would be useful for them to cooperate.

When we start to observe some part of the reality surrounding us, isn't it a kind of demonstration of "complex decoherence"? The only difference is that now we are not looking for the emergence of classical features from the "quantum soup", but for the emergence of classical features from the "*complex* soup" – made of intricate interconnections, hierarchical structures, adaptive loops etc. When we cut off the piece of complex reality that we observe, study, describe or model, couldn't it be the case that we adopt only one possible *history* of the system, leaving the rest aside?

We do not want to say that complexity can be identified with "quantum-ness". The mathematical theories developed in quantum mechanics are hardly transferable anywhere else. However, if we do not take things too strictly and stay almost only within verbal interpretations of these theories, we

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[222] Penrose, R. (1991) In: *Quantum Implications* (Essays in honour of David Bohm), ed. by B. J. Hiley and F. D. Peat, Routledge.

can easily replace the word ‘quantum’ by the word ‘complex’ and read these “stories” in another context. First, it would help us to become more familiar with complexity itself; second, it could give us inspiration on how to deal with complexity, and third, it confirms our intuition that the world is one continuum, ruled by the same laws. This is a step toward an interdisciplinary approach to the world, which we find much more useful than reduction, dividing the world into “sub-worlds”, e.g. quantum, classical, complex, relativistic etc.[223]

Since mathematics is from one side a game of numbers and symbols, it gives the opportunity to create countless numbers of fanciful worlds, that can be found in reality or not. Why is this so? Why does true, natural complexity, i.e. life, demand the “edge-of-chaos” pattern? Why are only a few systems – created by cellular automata – realised in the world, although with computers, we are able to create a huge number of different ones, even whole universes? These are questions that we met in the course of this chapter. In the section devoted to quantum mechanics some possible answers are sketched. We do not want to say that we believe in the reality of these theories. Nevertheless, they represent a successful attempt to explain these things, and even to produce some exact mathematical theory around the problems.

Quantum computation and human’s consciousness

The workings of the human mind have historically been described as metaphors of contemporary information technology. In ancient Greece memory was seen as akin too a “seal ring in wax” and in the 19th century the mind was seen as a telegraph switching circuit. In this and the previous century the classical computer has been the dominant metaphor for the brain’s activities. If quantum computation becomes a technological reality, consciousness may inevitably come to be seen as some form of quantum computation.[224] Indeed, enigmatic features of consciousness have already led to proposals for quantum computation in the brain (Hameroff: http).

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[223] The theme of reductionism will be discussed in the next chapter.

[224] One of the physicists who pointed out that quantum computation is capable of specific applications beyond the reach of classical computing was P. W. Shor – see his P*olynomial time algorithms for*

Conventional explanations portray consciousness as an emergent property of classical computer-like activities in the brain's neural networks. The current leading candidate for a computer-like "neural correlate" of consciousness involves neuronal circuits oscillating synchronously in the thalamus and the cerebral cortex. Higher frequency oscillations are suggested to mediate the temporal binding of conscious experience.[225] But how do neural firings lead to thoughts and feelings? Hameroff asks.

Conventional ("functionalist") approaches fall short on the mind's enigmatic features, he continues. These include:

- the nature of the subjective experience of our "inner life";
- the "binding" of spatially distributed brain activities into unitary objects in vision, and a coherent sense of "self";
- the transition from pre-conscious processing to consciousness;
- non-computability;
- free will.

Functionalist approaches generally assume that conscious experience appears as a novel property at a critical level of computational complexity. At first glance, this would seem to deal with issues of consciousness, however, it has neither been identified nor predicted, and there are no apparent differences in electrophysiological activities between non-conscious and conscious activity. Regarding the nature of experience, functionalism offers no testable predictions.

The problem of "binding" in vision and self is often attributed by functionalists to temporal correlation, but it is unclear why temporal correlation *per se* should bind experience without an explanation of experience. As functionalism is based on deterministic computation, it is also unable to account for non-computability or free will. To address these issues, various

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discrete logarithms and factoring on a quantum computer. In: Algorithmic Theory. 1st Internat. Symp., ANTS1 Proc., Eds. L. M. Adleman, M. D. Huang, Springer Verlag, Berlin 1994.

[225] Cf. Singer et al., *Formation of cortical cell assemblies*. Cold Spring Harbor Symposia on Quantitative Biology 55:939952 (1990); Gray, J. A., *Creeping up on the hard question of consciousness*. In: *Toward a Science of Consciousness II The Second Tucson Discussion and Debates*. Eds S Hameroff, A. Kaszniak, A. Scott (1998) MIT Press, Cambridge MA, pp. 279-291.

proposals have been suggested in which *macroscopic quantum phenomena* are connected to the brain's known neural activity.

Complexity, which occurs everywhere in our surroundings and, moreover, is an inherent part of ourselves, represents a great challenge for us to somehow grasp it and deal with it. The mere statement that it exists cannot satisfy us. Facing and coping with complexity has always accompanied people, even though they may not always have been aware of it. It has not been long since people first complexity as an individual category, and started to pursue complexity studies consciously. And of late they do it mostly (practically entirely) with the help of computers.

It appears, however, that nature's complexity is endless, and as such it is not comprehensible either to humans or to machines – which are nothing more than human products.[226] So, when dealing with complexity we must always accept some of the following rules:

- to choose a particular distance or angle for observing a given system;
- to chose only some convenient and promising questions;
- to be aware of one's own insufficiency, as well as that of computers, to experience the whole complexity of the given system;
- to make some reductions when approaching complexity;
- to be aware of the insufficiency of models developed by us for dealing with complexity;
- not to despair of the chance of overcoming these problems, since there is always a chance![227]

Nevertheless, in this chapter we did not only show the problems and difficulties connected to coping with complexity, but also many positive and promising approaches and theories that had been developed in the range of complexity sciences. We must again repeat a lot has already been done in

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[226] It does not have to be the case for the Complexity Daemon but it does not help us much. We do not have other chance than to stay as we are and therefore we can leave such considerations smoothly aside.

[227] Especially last two points, i.e. the problem of reductionism and getting out of this complicated situation, will be a subject of the next chapter.

this direction and the research still continues rapidly. No-one is able to say today what new will be done in the future and where this process will stop – if ever.

Even though the dream of a unified theory of complexity is still far from being realised, great achievements have been accomplished within the individual scientific fields. It is not our aim to repeat now all of those that have been mentioned in the previous paragraphs, but we will make a brief stop at one of them, i.e. quantum mechanics, because it is of special interest to us for reasons that will soon become clear – we hope.

Quantum mechanics probably most urgently felt the necessity to somehow deal with the problem of “reduced reality” that is either directly observed by us or in our experiments and the “far-exceeded reality” that is suspected of being around us (and within us). How it is possible and why it is so that we observe only a small part of this endless reality? What are the mechanisms that “reduce” it in our eyes? And what is the actual nature of this “complete” reality? What role do we play in it as observers?

These are examples of questions that are certainly not typical for natural science. We even dare to say that besides philosophy – which is usually is designated to dealing with such questions – one would hardly find another example of an effort to solve them rigorously, and what is more, in the language of mathematics! All the theories mentioned here, i.e. the theory of decoherence, Many Worlds Theory, the theory of consistent histories, etc. are great strides made in this direction and we are strongly convinced that they provide far-reaching consequences for the general theory of complexity. This is a very important issue requiring another comeback in the following text.

VI REDUCING THE IRREDUCIBLE

Recently all the newspapers and the main evening news carried information about the auction of the components of the Concord aircraft that took place in Paris. This machine was very popular as the first and last supersonic passenger aircraft and its dismantling caused feelings of sentiment in many people. It also became a valuable catch for collectors. One can well suppose that after a few years its value will be many times greater than now. For all of these reasons thousands of people went to Paris to participate in this auction. All of them with just one thing in mind: to at least get a small part of this famous aircraft.[228]

Even though on the day of the auction the aircraft actually did not any longer exist – for it had been already been taken apart– the people standing around did not see it. On the contrary, they saw it as a whole, its beauty and glory in each small part.[229]

From this story one can draw the following conclusion: *a machine that is built up from distinct parts can be reduced to those parts without loosing its machine-like character*. But, this certainly does not work for complex systems.

The Middle-Ages are known for its interest in collecting relics. All the bigger churches and most emperors wanted to have at least part of the body of their favourite prophet or saint. People hunted for pieces of bone, and teeth; some were even faking them – it was a booming business at that time.

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[228] Reporters said that the biggest interest was paid to wings a the pilot's seat.

[229] It is another very interesting phenomenon declaring people's mature for imagination and "actualization" of things existing only in the state of potency. It seems as if every component of the aircraft bore along also "aura" of the whole machine and people were able to see it. One single screw got the power to transmute from "an ordinary screw" (as such it had been certainly considered by people not involved in the action) to "A Part Of the Concord".

Nevertheless, before all of this can happen one fundamental condition had to be fulfilled: The prophet had to be dead. All of these “collector’s activities” could only start after he or she had died or – even more often – had been killed. Then the dead bodies were divided and sent into different corners of the world. Something important, however, has been lost: the prophet’s mind, feelings, and emotions, i.e. the attributes that constituted his personality as a living being.

Now imagine that after few years someone very rich appears and decides to buy all of the components of the Concord aircraft back from the collectors and tries to reconstruct the machine again. To be successful he needs two things: to get *all* of components, and to have a plan that would tell him exactly what the aircraft looked like.

Suppose that he has such a plan. What do you think? Will he succeed to construct the complete Concord? Probably not, even though he theoretically could. There is no obstacle in principal why he could not manage it. The reason is that the Concord aircraft is so huge, and composed of such an enormous number of parts that our enthusiast would probably not be able to collect all of them up to the last and smallest screw.

The situation would be even worse if this man had decided to reconstruct John the Baptist for example. Here other factors come into play. First, no “plan” of John the Baptist has ever existed (at best, in God’s mind, perhaps), so one criterion fails at the very start of the exercise. Second, although the preserved “parts” of John the Baptist are probably not so many as in the case of the Concord they, are still more than one can easily collect. Third, the most important part of him is beyond retrieve, lost at the moment of his death and there is no possibility of getting it back.

The statement that one can reconstruct the full reality of something from its fundamental components and laws is called the *constructionist hypothesis*. Even though it certainly works in some particular and simple cases, it breaks down when confronted with a) scale and b) complexity.

This is a crucial point, since everything surrounds us – including ourselves – is composed of a huge number of parts, and/or is complex, or even bears both of these characteristics. This is a fact that we must accept and accordingly we must decide which strategy of knowing the world to adopt.

Historically, there are two main streams of the scientific[230] approach that one can choose: *reductionism* and *holism*.

1. Reductionism versus holistic approaches to knowing the world

The first suggestion of a reductionary approach already came from the first Grecian philosophical school of Miletus. Thales[231] first put the question of the foundation, cause and unchangeable nature of everything is. With this he started a new way of thinking that is still topical today: to reduce an intricate and unclear reality to something simpler, or even to the simplest element that would (in the best case scenario) be eternal and invariant. This idea appeared to be so promising that until now it has been at the centre of science, and most generally at the centre of rational "western" thinking.

With the help of the following examples we shall try to show that the interpretation of some phenomenon (either of the world as a whole or of particular things) usually has the attributes of reduction. For instance, when we want to solve a problem mathematically, we must formulate it in mathematical terms, i.e. reduce it to the quantitative relations of some chosen quantities (and neglect the rest of them). In physics we also reduce the given data input to physical entities, and consequently we reduce these physical entities to the mathematical ones. The same happens, for example, when solving some economical theories. When we deal with a problem of law, we reduce the system to the elements of the law system (legal subjects, legal relations etc.); with aesthetic considerations we reduce the system to aesthetic categories. The explanation of grammatical phenomena consists in the reduction to particular grammatical figures.

Reductionism in its strongest form regards the world as a series of reductive levels (social groups, multi-cellular living things, cells, molecules, atoms, and finally as the smallest parts, the elementary particles) where it is

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[230] 'Scientific' in the broadest sense of the word, including 'pre-scientific'

[231] aprox. 624 – 546 BC

expected that the laws at one level can be reduced to laws at the lower level. A subclass of reductions is termed *micro-reductions*.

In the 1930s the logical positivists especially advanced the idea of the Unity of science, and it was maintained until the late 1950s (Andersen 2001:153). In 1958 Oppenheim and Putnam wrote in their paper "Unity of Science as a Working Hypothesis[232]

> It is not absurd to suppose that psychological laws may eventually be explained in terms of the behaviour of individual neurons of the brain; that the behaviour of individual cells – including neurons – may eventually be explained in terms of their biochemical constitution; and that the behaviour of molecules – including the macro-molecules that make up living cells – may eventually be explained in terms of atomic physics.

When we try to explain any unknown phenomena we reduce them to *known* ones. When we succeed, we think that we understand these new phenomena. Such "known phenomena" create sc. reducing systems, and to some extent they are subjective – for everyone knows something different. From this point of view there is a plurality of such sets of reducing theories and implicitly also a plurality of possible explanations.

Reductionism is an essential constituent of cognition, since it enables us to easily understand difficult things. Thanks to reduction we can understand the way that a computer works, for example.[233] However it is beyond human ability to understand the operation of a computer in its entirety, to understand every detail of the operation of every component and their mutual connectivity, without any reduction.

Reductionism has become a powerful tool of human knowledge; we apply it at almost all levels of knowing. Reducing enables to rationally grasp many difficult problems, but on the other hand it also has its negative side. Every reduction naturally means simplifying, and consequently also distortion. When reducing, something must always be neglected, and this can later turn out to be detrimental to us – especially when we forget it. It really happens

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[232] Oppenheim, P., Putnam, H. In: *Concepts, Theories and the Mind-Body Problem*, Minnesota Studies in the Philosophy of Science, Vol. II, University of Minnesota Press, p. 7.

[233] Notice that such a reducing basis is different for the ordinary user, for the programmer, for the software engineer, for the hardware engineer, for the physicist etc.

quite often that people do forget about the neglecting and simplifying that they have done; even more often than we would imagine. Besides the effect of "forgetting", there are also frequent cases of "unconscious reduction". This is even worse, because in this case, people identify the simplified picture with reality itself. Then what usually happens is that we are surprised when a paradox appears that we cannot explain within the frame of this reduced theory. This is a signal that "something is wrong".[234]

Reductionism can be considered on two levels: a) inside some particular system (in the framework of physics, biology, sociology, etc.) – we will call it *inner reductionism* and b) on the interdisciplinary level (e.g. the reduction of chemistry to physics, sociology into biology, etc.) – here we will speak of *external reductionism*.

Internal reductionism is usually considered as something obvious and as such it is not seen as reductionism in the proper sense. Often it is an unconscious process; the reduced picture of reality is then regarded as the reality itself.

On the contrary, external, interdisciplinary reductionism is usually seen as true reductionism. One of the reasons is certainly psychological: science is usually perceived through the prism of individual, relatively independent branches (physics, chemistry, biology, etc.) and relevant specialists from particular branches are usually unhappy when specialists from the others intervene in their problems. For instance, when a chemist or physicist wants to reduce biology to his or her domain, they will be designated by the abusive name "reductionist".

As with any other tool, reductionism can also cut two ways. It uncovers something to our eyes (some particular consequences or expected order), but conversely, it hides the other aspects (other consequences; unexpected order). The point is what do we reduce to what, and what theories do we use?

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[234] This is a case of sc. vulgar materialism: an advocate of this ideology reduces all complex systems (including living systems and man) to the basic physical entities, and "forgets" in the meantime that he has neglected important and intricate mutual connections of the individual elements the system is composed of. However, these complex relations represent the foundation that makes living beings alive. Especially when it comes to beings that are alive, he looses the phenomenon of life itself and he works with only a set of the components; at the most with some mechanical system.

Therefore, using reductionism should also be subject to *rational criticism*. To do so, we must first be aware *what* we do – i.e. that we reduce reality. When we are unaware of this reduction critical reflection is not possible, and often we are sooner or later confronted with a paradox.

Reductionism was already rejected by some scholars in the mid-19th century. John Stuart Mill, for example, argued that the properties of molecules could not be derived from the properties of their constituent elements[235] (Andersen 2001: 153):

> …the chemical combination of two substances produces, as is well known, a third substance with properties different from those of either of the two substances separately or of both of them taken together. Not a trace of the properties of hydrogen or of oxygen is observable in those of their compound, water.

Likewise, Mill denied that the phenomenon of life could be derived from the constituents of a living body[236]

> To whatever degree we might imagine our knowledge of the properties of the several ingredients of a living body to be extended and perfected, it is certain that no mere summing up of the separate actions of those elements will ever amount to the action of the living body itself.

The question emerges: what are the fundamental, the simplest principles for all other things to be reduced to?[237] Actually, searching for a fundamental reductive basis is the primary methodological step in every scientific discipline. The reason is that every discipline is defined by this fundamental reductive basis. For physics this basis is composed of physical entities (and their mutual relations, described by physical laws), for law these are legal subjects and their relations, for aesthetics, aesthetic terms, etc.

We also adopt the reducing approach in our ordinary lives (usually unawares). We use the subjective "basic entities" that are known to us and rather individual for our personal point of view. This "reductive basis" is

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[235] Mill, J. S. (1843/1973) *A System of Logic*, reprinted in 1973, London: Routledge & Kegan Paul, p. 371.

[236] Ibid. P. 371f.

[237] This question can well be considered the most fundamental question of all epistemological disciplines – scientific, philosophical or others.

however only intuitively and vaguely defined. Many such “subjective reductive bases” are often incompatible mixtures of intuitive basic elements and basic elements that we have taken from different systems that we have met (most often from partially understood physics).[238]

In the matter of reductionism, western and eastern ways of thinking look different from the very beginning. Eastern philosophy advocates unreduced knowing - almost all eastern thinkers state that the nature of our world cannot be reduced to a few simple principles. They are opposed to spontaneous reductionism. In its place they advocate consciousness of the intricate and complex, mutually entangled aspects of nature, and even their interconnection with our mind. This approach is called “entire” or *holistic*.[239]

Although the holistic point of view offers inspiration, it has not asserted itself as a basis for science and technology. For, to rationally grasp the world in its endless complexity is not possible and holism confines itself to some intuitive perception of the totality and interconnectivity.

Different kinds of reduction:

Probably the most fundamental topic of discussion when it comes to reduction is the one that addresses the question of *ontological reduction*, i.e. whether entities of one domain are composed of the entities of another domain. An important example of this type of debate is the debate, that started at the beginning of the 20th century, on whether all biological entities are composed entirely of physicochemical entities, or if there are special forces that are peculiar to living entities, as, for example, biologist H. Driesch[240] and other vitalists argue (cf. Andersen 2001: 154).

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[238] Moreover, it is obvious that this “basic-ness” of foundations is only relative. This point is mainly stressed by many post-modern philosophers. We usually understand the term “basic” as “simple”, “primitive” and as something that is subjectively closest to us. What is difficult, on the contrary, is what is “far away” from us; we must turn it into the simple and compose it from simple entities. However, “simplicity” and “difficulty” are not objective characteristics. The traditional *hierarchy of intricacy*, starting from mechanics, physics, chemistry, biology, psychology and continuing to the social sciences, and the traditional characterising of life as “the most intricate form of the movement of matter” are not valid absolutely. They represent relative categories to some extent. For example, the behaviour of our living (i.e. the most complex) pet dog can be more understandable and more “simple” for us than the behaviour of a non-living flywheel or subatomic particle.

[239] ‘Holism’ is derived from the Greek word ‘holos’ – the whole.

[240] Driesch, H.(1908) *The Science and Philosophy of the Organism*, London: A. C. Black.

Epistemological reduction on the other hand deals with the question whether the laws or theories of one domain can be derived from the laws or theories of another domain. For instance, whether the laws of thermodynamics can be derived from the laws of statistical mechanics, or whether the laws of classical mechanics can be derived from the laws of the theory of relativity.[241]

Another distinction of reduction is based on reductive relations. *Successive reduction* is a reductive relation between historically successive theories addressing the same object-domain, for example classical mechanics and the theory of relativity. Inter-level reduction, on the other hand, is the reductive relation between theories that address object domains at different levels of complexity, for example the level of biological organisms and the level of molecules.

Usually, a theory that is reduced to another is called a *secondary theory*, whereas the reducing theory is called the *primary theory*.

Hanne Andersen adds in his brilliant paper (Andersen 2001: 154) that one should note that the usage of the term 'reduction' differs significantly in science and in philosophy. Philosophers usually speak of reducing less fundamental theories to more fundamental ones and would for example, in discussing classical mechanics and the theory of relativity, discuss the reduction of the former to the latter. Scientists, on the other hand, discuss the same case by saying that under certain circumstances, velocities much smaller than the velocity of light, the special theory of relativity is reduced to classical mechanics.

In the recent decades, the philosophical part of the reduction debate has largely focused on the possible reduction of mind states to brain states, and on the possibility of reducing biology to a chemical level, especially the reduction of Mendelian genetics to molecular biology.

In recent years, a specific debate has emerged with the development of the Human Genome Project. The application of the techniques of molecular

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[241] Some authors also distinguish a third kind of reduction – *methodological reduction* – which concerns the strategy of research, for example, whether in the study of biology we should always proceed by investigating the underlying process, or whether we must study higher as well as lower levels of organization. Cf. Ayala, F. J. (1974) Introduction in *Studies in the Philosophy of Biology. Reductionism and Related Problems*, Berkeley: University of California Press.

biology to problems of human diseases had led to intense discussions on whether diseases such as schizophrenia, special forms of cancer, or complex behaviour patterns like alcoholism or homosexuality can be fully explained by theories of molecular genetics alone.

The current situation with respect to the question of reductionism, was nicely described by philosopher of mind, Jaegwon Kim:[242]

> Expressions like ‘reduction’, ‘reductionism’, ‘reductionist theory’, and ‘reductionist explanation’ have become pejoratives not only in philosophy, on both sides of the Atlantic, but also in the general intellectual culture of today. They have become common epithets thrown at one’s critical targets to tarnish them with intellectual naiveté and backwardness. To call someone ‘a reductionist’, in high-culture press if not in serious philosophy, goes beyond mere criticism or expression of doctrinal disagreement; it is to put a person down, to heap scorn on him and his work.

2. Science and reality

Now we will focus on the question of how close we can get with *our* answers to the factual questions posed, and the *reality* that they strive to comprehend.

According to *scientific realism* science describes the *real world*. This means that the theoretical terms of natural sciences should refer to real physical entities and describe their attributes and behaviours. For example, if we want to obtain information on ‘electron spin’, we will probably try to have a look a textbook of atomic physics. In this special case we are thus referred to the natural sciences for an answer, for ‘electron spin’ refers to a behavioural characteristic of a real – though unobservable – object, i.e. an electron. In other words, the declarations of science are factually true generalizations about the actual behaviour of objects that exist in the world.

The last statement seems to be quite natural to all of us who feel comfortable with scientific realism and actively work, or used to work, in a scientific field. However, there is one urgent question one cannot overlook:

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[242] Kim, J. (2000) *Mind in Physical World. An Essay on the Mind-Body Problem and Mental Causation*, Cambridge MA: MIT Press. Quoted according to (Andersen 2001: 155).

can our science be considered as a correct science and does it offer the definitive “last word” on the issues it studies?

This question is pretty tricky, since there are nearly as many opinions on this issue as people dealing with it. It is a matter of fact that science is not a static system, but a dynamical process. A lot has been written about the history and methodology of science. Probably the most famous book devoted to this issue is *The Structure of Scientific* Re*volution* written by Thomas Kuhn (Kuhn: 1970). The main idea can be summarized as follows: the process of the historical development of science is not cumulative,[243] but happens in “jumps” – when the right time comes the old theory is completely abandoned and thrown away as useless and a new one takes up its place.

Although many objections can be raised against Kuhn’s theory, too, one thing is certain. The history of science gives evidence of many cases where theories were found to be wrong, and naturally it does not stand science in good stead. So it appears that we should maintain a clear distinction between *our conception of reality* and *reality as it really is*.

Given the equation:

our (conception of) reality = the condition of things as seen from the standpoint of “our *putative* truth” (= the truth as we see it from the vantage point of the science of the day)

it appears – as N. Rescher states (Rescher 1998: 124) – that there is little justification for holding that our present-day science describes reality and depicts the world as it really is. The world *that we describe* – he continues – is one thing, the world, *as we describe it* is another, and they would coincide only if our descriptions were totally accurate – something that we are certainly not in a position to claim.

Correctness in the characterization of nature can best be achieved, not by *our* science, but by *perfected* or *ideal* science. The definition of scientific realism should therefore be re-formulated to “what an ideal or perfected science takes the world to be like”.

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[243] Cumulative a means gradual, smooth transition between old and new theories, where the latter makes use of the achievements of the former.

This does not mean that we intend to take up the position of scepticism; quite the opposite. We are still sticking with realism and – in accordance with N. Rescher – in two senses, even:

- A realism that is realistic about our capabilities of recognizing that we are dealing with the efforts of an imperfect creature, trying to do the best it can under the circumstances;
- A realism that recognizes the mind-transcendent reality of the "real world", that our own best efforts in the cognitive sphere can only manage to rather imperfectly bring under control. We recognise that no matter how far we manage to extend the frontiers of natural science, there is more to be done. In the case of vast complexity reality even outruns our cognitive reach. Reality is just too multi-faceted for us to cognitively tame it more than partially (Rescher 1998: 126).

3. A turning point in epistemology

To start this section we begin with the question "What is an epistemology?" According to H. H. Patee (Patee 1998: 23) it is a theory or practice that establishes the conditions that make knowledge possible.

There are many epistemologies. Religious mystics, and even some physicists – Patee observes – believe that higher knowledge is achieved by a state of ineffable oneness with transcendent reality. However, while this may work for the individual – Patee stresses – it does not work for populations that require *heritable* information or common knowledge that must be communicable.[244] Knowledge is potentially useful information about something. Information is commonly represented by *symbols*. Symbols stand for, or are about, what is represented. Knowledge may be about what we call reality, or it may be about other knowledge. It is the implementation of "standing for" and "about" – the process of executing *the epistemic cut*.

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[244] Cf. Born, M.(1964) *Physics in my Generation*, Springer-Verlag, NY, pp. 132-146.

We are going to deal with epistemic cuts here, separating *knowledge of reality* from *reality itself*, e.g., description from construction, simulation from realization, mind from brain.

Physics

“The requirement for heritable or objective knowledge is the separation of the subject from the object, the description from the construction, the knower from the known. Hereditary information originated with life with the separation of description and construction, and after 3.6 billion years of evolution this separation has developed into a highly specialised and explicit form at the cognitive level”, H. H. Patee states. Likewise, von Neumann states (von Neumann 1966) on the epistemology of physical theory:

> … we *must* always divide the world between the two parts, the one being the observed system, the other the observer. The boundary between the two is arbitrary to a very large extent… but this does not change the fact that the boundary *must* be put somewhere, if the method is not to proceed vacuously….[245]

And H. H. Patee continues: “In physical theory, the observer is *formally* related to the observed system only by the *results* of the measurements of the observables defined by the theory, but the formulation of the theory, the choice of observables, the construction of the measuring device, and the measurement process itself cannot be formalised.”

No matter where we divide the world into observed and observer, the fundamental condition for physical laws is that they are invariant to different observers, or to the frames of reference, or states of observers. Laws, therefore, hold everywhere – they are universal and inexorable. In addition to the invariance of symmetry principles, the laws must be separated from the initial conditions that are determined only by measurement.

Measurement requires another category of knowledge called *boundary conditions*. Initial conditions cannot be *measured*, nor can boundary conditions be *constructed*, with the deterministic precision of the formal

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[245] Cf. our chapter V, 2.

dynamical laws. Thus, this category of knowledge requires *statistical laws*. Statistical laws however introduce one of the great unresolved fundamental problems of epistemology.[246] The dynamical laws of physics are all symmetric in time, and therefore reversible, while statistical laws are irreversible. Formally, these two types of laws are incompatible. It is even difficult to relate them conceptually. As Planck says (Planck 1960: 64):

> For it is clear to everybody that there must be an unfathomable gulf between a probability, however small, and an absolute impossibility»

And then, a few rows down:

> Thus dynamics and statistics cannot be regarded as interrelated.

It appears that the epistemic cut in physical theory falls directly in Planck's "unfathomable gulf" between dynamical and statistical laws. The possible trajectories of the world are dynamically described by reversible laws, but any explicit knowledge of a trajectory requires observations or measurements, described by irreversible statistical laws. This is the root of the measurement problem in physical theory. Von Neumann described it as follows (von Neumann 1955: ch. VI):

> An epistemic cut must separate the measuring device from what is measured. Nevertheless, the constraints of the measuring device are also part of the world. The device must therefore be describable by universal dynamical laws, but this is possible only at the cost of moving the epistemic cut to exclude the measurement. We then require a new observer and new measuring devices – a vacuous regress.

It is also important to understand that invariance and compressibility are not themselves laws, but are necessary epistemic conditions to establish the heritability, objectivity and utility we require of laws (Patee 1998: 28). If the entire world in all its details were really invariant there would be nothing to observe.[247] No epistemic cut would be possible and therefore life could not exist, except perhaps in a mystical sense. It is only because we divide our knowledge into two categories, dynamical laws and initial conditions, that invariance itself has any meaning. How we choose this cut intellectually is

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[246] Cf. above sections devoted to quantum mechanics.

[247] See also Curie, P. (1908) *Oeuvres*, Gauthier-Villars, Paris, p. 127.

largely a pragmatic question, although there is also a strong aesthetic component in the choice.

Life and artificial intelligence

We should start our considerations about epistemic cuts in the “life-sciences” with thoughts on life itself. It is obvious that the nature of life represents one of the as yet unresolved, centuries-old problems. What we know is only that life depends on matter, but it is *not* an inherent property of matter. Life is peculiar because it is completely different from nonliving matter.

The previous sentence – even though trivial at the first glance, – has led us to a fundamental issue: when we start to talk about difficult, i.e. complex things, we spontaneously look for a *comparison* as a tool for characterising things. This is the point that we want to talk about. The more complex the object, the deeper the gap between knowledge of this object and the object itself.[248]

Exactly the same principle is valid for *artificial life*, but what do we compare artificial life to? At first the founding characterisation of artificial life was based on comparing “life-as-it-could-be” with “life-as-we-know-it” (Patee 1998: 23). Such abstract characterisations were, however, soon abandoned, because it did not clearly separate science fiction and computer games from physical reality (ibid.).

An alternative view of artificial life uses computation to control robots in the physical world. Although this approach seems to be far from touching on fundamental issues, it has the huge advantage in a practical sense of using the physical world at face value. For, “it is very hard to simulate the actual dynamics of the real world” – as R. Brooks points out in (Brooks 1992: 3).

H. H. Patee answers this objection as follows:

> We can only compare life to non-life, that is, to the nonliving world from which life arises and evolves. Artificial life must be compared with a real or an artificial nonliving world. Life in an artificial world requires exploring what we mean by an alternative physical or mathematical reality.

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[248] This is also how we defined the epistemic cut.

Metaphorically one can say (according to H. H. Patee) that life is matter with meaning. Less metaphorically, organisms are material structures with memory, by virtue of which they construct, control and adapt to their environment. Further, open-ended evolution requires an epistemic cut between the genotype and phenotype, i.e. between description and construction. The logical necessity of this epistemic cut is also the fundamental point of von Neumann's self-replicating automaton (von Neumann 1966).

All of evolution, emergence, adaptation and extinction depend on how quickly and efficiently the variations in the genotype can be implemented in phenotypic functions. How does a symbolic-sequence space map into a physical-function space? Whatever the answer is, it is significant that, even at the simplest level, the implementation entails a computationally intractable problem.

The advantage of the autonomous robotics approach to artificial life is that it avoids these intractable computational problems in the same way that real life does – it harnesses real physics.

In traditional philosophy, epistemic cuts are viewed as problems only at the cognitive level. They are called problems of reference, or of how symbols come to "stand for" or to "be about" material structures and events.[249] However, the reversed question is just as important (at least): How do material structures ever come to be symbolic? (Patee 1998: 26) That is to say, one can suppose that if we fully understood how molecules become messages in cells we would have some understanding of how messages have meaning.

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[249] See for example Whitehead, A. N. (1927) *Symbolism: Its meaning and Effect*, Macmillan, NY.

4. Common sense

It is a hundred years already, since the fact was discovered that it is not possible to describe the world of atoms with the laws of ordinary physical experience. To formulate this “new physics” exactly became the task of the next thirty years. The quantum theory that was born in those days is undoubtedly brilliant in its universality and formally excellent construction. However, there is one difficulty connected to it, which causes headaches for many people: its incompatibility with sc. *common sense.*

Let us imagine a journalist who has been asked to write about quantum mechanics for non-physicists. He opens some of the many textbooks on quantum mechanics and starts to go through the conclusions, non of which he understands. He reads, for example, that:

> There is nothing that could be called the trajectory of an electron. The notion of trajectory is of no use in the microworld.
>
> The electron moves along all possible trajectories in one instant. The contributions from all trajectories mutually interfere.

And somewhere else:

> Quantum mechanics does not speak of “objective reality” but only of the results of measurement. Wave function $|\psi>$ represents only the maximal available information about the quantum system.
>
> Wave function $|\psi>$ represents a full reality of the quantum systems, reality that is of an abstract character.

The journalist will probably be struck by these apparently contradictory statements and confused as to which of them he should choose. Or perhaps he does not understand them properly? This is not his fault. Even if this list of randomly chosen statements were given to a group of specialists to corroborate, they won’t reach any agreement.

Since the very beginning of its existence, quantum mechanics has been living two “lives”. In the first one, only calculations are carried out, and results are formulated in the language of mathematics. Here everything goes according to plan and no one needs to hesitate about its accuracy. In the second "life", what happens on a paper and in experiments is translated into common language, with the aim to bring it closer to common experience; this is the moment where problems appear.

From the point of view of our "natural experience", there are many strange things in quantum mechanics. The quantum world is completely different from the world we live in and experience daily. It is often said that the majority of these discrepancies are only caused by the fact that our expectations and opinions have been formed by contact with a macroscopic world, and therefore they work well in this world and fail when applied to the microworld. It seems that if we want to deal properly with quantum systems, we must leave our common sense aside. But this does not necessarily need to be true, as we will see.

In the twentieth century science reached some basic principles, particularly in quantum mechanics and the theory of relativity. Even if they are not complete (we do not have a "final theory", cf. chapter V), they are sufficient for generating all the essential features of macroscopic phenomena as consequences. Physics has, to some extent, reached the *basic principles* that were acquired by Locke and Hume, for instance, who speculated that our representation of reality – the possibility of describing it with *language* and the use of *common sense* – follow from the observed *regularities* in our surrounding world (Omnès 1995: 732).

In the previous chapter we gave a brief overview of two "modern" interpretations of quantum mechanics: Everett's Many World Theory (MWT) and the Theory of Quantum Histories. Although they are both certainly very interesting, they have never been fully appreciated, and many scientists still prefer the traditional Copenhagen interpretation of quantum mechanics, which we mentioned in chapter III. The reason consists mainly in three facts: The Theory of quantum histories[250], is especially, more technical and mathematical than the Copenhagen interpretation, because it began with technical discoveries (the decoherence effect, the notion of consistent histories) and the existence of a specific logical framework for discussing

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[250] It is sometimes also called Theory of Consistent Histories, Decohering Histories or Logical Interpretation, since it was discovered or developed independently by various people.

them. The extension of these ideas to encompass classical physics had to rely upon unfamiliar mathematical techniques, or use new concepts such as *decohering histories*.[251]

Though both of them share as many features as they differ, one main difference should be stressed here: According to Bohr (as a main representative of the Copenhagen interpretation) every interpretation consists in reconciling the abstract formalism of the basic principles with ordinary language, allowing one to express and communicate experimental situations and facts.[252] There is already a difference between the two interpretations here (Omnès 1995: 724). One claims that these two macroscopic features and the classical rules that they obey follow from the basic principles of quantum mechanics. Accordingly, interpretation does not consist in reconciling the principles with what may be called *common sense*, but in *deriving common sense from the principles*.

The consequences of this are fundamental: the relation between physics and philosophy of knowledge is now reversed. The principles that have been reached by science are now primary. Many philosophical principles, on the contrary, are more or less general rules, abstracted from common sense, while this "new interpretation" of quantum mechanics – as some people believe – represents a "proof" of common sense from physical principles.

It is true that one very sees often articles or even books that criticise quantum mechanics – or at of its features at least– on the basis of philosophical principles that are based on the *common sense*. This approach is, in truth, a reversal: sc. *common sense* is built up in accordance with physical principles.

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[251] It is beyond the scope of this work to explain this theory in all its detail.

[252] Cf. Bohr, N. (1958) *Atomic Physics and Human Knowledge*, Wiley, New York, N. Y..

5. Different ways to knowledge

Although people have been very successful at modelling and even copying complexity – especially in the field of artificial intelligence – there still seems to be something missing. Over the past fifteen years behaviour-based artificial creatures have been built, situated in the world like insects,[253] and recently robots have been built that have human-like social interactions[254]. However, one never quite forgets that these systems are machines and not alive. These models are built to better understand the biological systems, but the models *never* work as good as the biology.

On the other hand, scientists have gotten very good at modelling fluids, materials, planetary dynamics, nuclear explosions, and all manner of physical systems. We can put some parameters into a program, crank it, and get accurate predictions of the physical characteristics of the modelled system. But we are not good at modelling living systems, neither small, nor large ones.

Perhaps we are missing something fundamental and currently unimagined in each of our various models. If this turns out to be the case we will need to have some new ways of thinking about complexity issues. As an analogy, suppose we are building physical simulations of elastic objects falling and colliding. If we did not quite understand physics, we might unfortunately leave out mass as a specific attribute of the objects. Their falling behaviour would at first seem correct, but soon as we started looking at the collisions we would notice that the physical world was not being modelled correctly.

What might the nature of this missing element be? One future possibility is that we will discover some general aspect of complex systems that is invisible to us right now. One might imagine that there is something on a par with the discovery a century ago of radiation, which ultimately led to our evolving understanding of quantum mechanics; or it may be that what is missing is simply some "*new mathematics*". It may be that we do not require any "new physics", but it might turn out to be the case that we are simply not

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[253] See Brooks R. (1999) *Cambrian Intelligence*, Cambridge, Massachusetts.

[254] See Breazeal C. (2001) *Designing Sociable Robots*, Cambridge, Massachusetts.

seeing some fundamental mathematical description of what is going on in complex systems.

A new mathematics

Mathematics is traditionally considered to be a kind of *science*. Roughly speaking, every science is characterised by its subject and methods. Mathematics, however, is special in this sense, for it does not have its own subject; its particularity rests in its method. Therefore, considering mathematics as a science is rather dubious. It is rather just a *method*.

Is mathematics only a useful method in the deductively built disciplines? It appears that this is not necessarily the case. There are situations where we can use mathematics without knowing the nature of the phenomena being studied – it is possible to create calculus suitable only to *manifestations* of such phenomenon. For instance, medieval astronomers were able to predict positions of planets in the sky with the help of mathematics without knowing that they rotate around the sun. There are many more similar examples. It appears as if the only suitable proto-mathematical activity (for example a suitable description of some situation) can often significantly influence both human knowledge and behaviour, even if no further calculus follows - i.e. a kind of “proto-mathematics” without any further mathematics (Vopenka 1971: 737).

A very good example of proto-mathematics is phonetic writing. It is possible to say that the discovery of phonetic writing is of importance in a manner that has no analogy in mathematics at all. Up to now, such descriptions have been used in mathematics where simple symbols represented atomic units – each having its own meaning. It could be represented by writing, where every word – i.e. atomic unit of language with its own meaning – is expressed by an individual sign. However, to disassemble words to phonemes (i.e. symbols), that bear no meaning[255] by themselves is something with no analogy in mathematics.

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[255] What is more, the sounds produced by reading the individual phones, is often only slightly similar to the sound of the whole word.

It is obvious that most of the natural scientists do not like working with vaguely defined terms. They prefer to identify studied terms with corresponding formal terms or even to identify a studied situation with a calculus that has been developed for the study of this situation. However, this attitude – promoting calculus to a state of reality – can be very dangerous. We should keep in mind we only obtain predictions about originally studied situations with the help of calculus. If we identify this calculus with studied reality we could obtain data with the help of this calculus. Nevertheless, there is always a possibility that we have chosen the calculus wrongly and that, therefore, our predictions are wrong as well.

A typical example of an incorrectly chosen calculus is provided by physics. Predictions obtained with the help of calculus originally developed in the framework of classical physics, are no longer reliable, and they need to be replaced with a new calculus, more suitable to the study of new physical situations.[256] Nowadays, the situation is even more complicated, for physics now solves such difficult problems, that they cannot be compared to past problems. Maybe the best way forward for physics would be to create its *own independent calculus*, regardless of contemporary mathematical concepts.

If we accept this idea in the case of physics, this appeal is more urgent in the case of complexity studies. Maybe, in the range of complexity we should also look for its own independent kind of "calculus", suitable for describing complex situations.

Linguistics variables

A very interesting approach to the analysis of complex systems was recently proposed by Lofti A. Zadeh (Zadeh 1973). His theory is based on the following ideas: to use "linguistic" variables in place of or in addition to numerical variables in system analysis, the characterisation of simple relations between variables by fuzzy conditional statements, and finally, the characterisation of complex relations by fuzzy algorithms.

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[256] As in the case of the transition from classical physics to relativity physics, for example.

As the author points out, the rapid development of computer techniques has stimulated an expansion in the use of *quantitative techniques* for the analysis of the majority of complex systems, e.g. economic, urban, social, biological and other types of systems. However, the humanistic – or human centred – systems are very tricky to deal with. Up to now the techniques that have been developed for *mechanistic systems* (i.e. physical systems governed mainly by the laws of mechanics, electromagnetism, and thermodynamics) have been adopted for them. Nevertheless, it is Zadeh's contention that such conventional quantitative techniques of system analysis are intrinsically unsuited for dealing with humanistic systems.

The basis for this contention rests on what might be called the *principle of incompatibility*. This principle simply says that as the complexity of the system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached, beyond which precision and significance (or relevance), become almost mutually exclusive characteristics. Precise quantitative analyses of the behaviour of humanistic systems do not have much in common with the real situation where humans, either as individuals or in groups, are involved.

An alternative approach outlined in Zadeh's paper is then based on the premise that the key elements in human thinking are not numbers, but labels of fuzzy sets – that is, classes of objects in which the transition from membership to non-membership is gradual rather than abrupt. The consequence of the pervasiveness of fuzziness in human thought processes is that much of the logic behind human reasoning is not the traditional two-valued or even multi-valued logic, but *logic with fuzzy truths*, fuzzy connectives, and fuzzy rules of inference.[257] Therefore, what we need – to be able to deal with these systems realistically – is an approach not based on any precise, rigorous mathematical formalism, but rather on a framework that is tolerant of imprecision and partial truths. Such an approach can be as follows: based on linguistic variables, conditional fuzzy statements and fuzzy algorithms.

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[257] This is the same conclusion that we found in the paragraph devoted to quantum mechanics.

A *linguistic variable* is defined as a variable whose values are sentences in a natural or artificial language. Thus, if *tall*, *not tall*, *very tall*, etc. are values of *height*, then *height* is a linguistic variable (Zadeh 1973: 28). This idea is supported by the fact that each word *x* in a natural language *L* may be viewed as a summarised description of a fuzzy subset M (*x*) of a universe of discourses *U*, with M (*x*) representing the meaning of *x*. In this sense, the language as a whole may be regarded as a system for assigning words, phrases, and sentences to the fuzzy subsets of *U*. For example, if the meaning of the noun *flower* is a fuzzy subset *M* (*flower*), and the meaning of the adjective *red* is a fuzzy subset *M* (*red*), then the meaning of the noun phrase *red flower* is given by the intersection of *M* (*red*) and *M* (*flower*).

If we regard the colour of an object as a variable, then its values *red*, *blue*, *yellow*, *green*, etc., may be interpreted as labels of fuzzy subsets of a universe of objects. In this sense, the attribute *colour* is a *fuzzy variable*, that is, a variable whose values are labels of fuzzy sets. It is important to note that the characterisation of the value of the variable *colour* by a natural label, such as *red*, is much less precise than the numerical value of the wavelength of a particular colour.

The main function of linguistic variables is to provide a systematic means for an approximate characterization of complex or ill-defined phenomena. In essence, by moving away from the use of quantified variables and toward the use of the type of linguistic descriptions employed by humans, we acquire the capability to deal with systems that are much too complex to be susceptible to analysis in conventional mathematical terms (Zadeh 1973: 29).

Fuzzy conditional statements are expressions of the form IF *A* THEN *B*, where *A* and *B* have fuzzy meanings, e.g., IF *x* is *small* THEN *y* is *large*, where *small* and *large* are viewed as labels of fuzzy sets. A *fuzzy algorithm* is then an ordered sequence of instructions which may contain fuzzy assignment and conditional statements, e.g., *x* = *very small*, IF *x is small* THEN *y* is *large*. Actually, fuzzy algorithms pervade much of what we do. We employ fuzzy algorithms both consciously and subconsciously when we walk, drive a car, search for an object, park a car, find a number in a telephone dictionary, etc. Furthermore, there are many instances of uses of what, in effect, are fuzzy algorithms in a wide variety of fields, especially in programming, psychology, management science, and medical diagnosis (Zadeh 1973: 38). According to Zadeh:

by relying on the use of linguistic variables and fuzzy algorithms, the approach provides an approximate and yet effective means of describing the behaviour of systems which are too complex or too ill-defined to admit of precise mathematical analysis. Its main application lies in economics, management science, artificial intelligence, psychology, linguistic, informational retrieval, medicine, biology, and other fields in which the dominant role is played by the animate rather than inanimate behaviour of system constituents.

Narrative knowledge

“All relevant knowledge is narrative knowledge.” Statements like this are more and more coming to the fore in discourses on organisational knowledge and its management. No doubt, recently organisational narrations have attracted a lot of attention. For instance, Communities of Practice are assumed to stir and to distribute stories told among experts – stories that contain and transfer “narrative knowledge” of that community. Similarly, studies on technical knowledge transfer have shown that service technicians exchange their experiences primarily in the form of narrations. “Oral culture” seems to have a major impact on the processing of knowledge in organizations.

These insights reflect on a more general level that organisations can be seen and analysed as complex webs of narrations. It is widely accepted by now that narratives are one of the basic elements in organisational sense-making processes. Storytelling is the preferred “sense-making currency” and the organisational memory system is also constituted, maintained and changed by stories. The focus on narrations seems to increasingly replace the conception of tacit knowledge that dominated the field for quite a while.

The notion of narrative raises a lot of questions concerning the form and function of narratives and how they are related to knowledge. Whilst the interest in narrative in organisational studies is relatively new, there is a long-standing tradition in literature discourse and in the arts in general.

Grand narrative or "master narrative" is a term introduced by Jean-François Lyotard in his classic work *The Postmodern Condition: A Report on Knowledge* (Lyotard 1984). Narrative knowledge is knowledge in the form of *storytelling*.

At the beginning of his book Lyotard states his "working hypothesis" as follows:

> the status of knowledge is altered as societies enter what is known as the post-industrial age and cultures enter what is known as the post-modern age. This transition has been under way since at least the end of the 1950's which for Europe marks the completion of reconstruction.

In tribal times, myths and legends formed knowledge of this type; such-and-such a mountain was just where it was because some mythic animal put it there, and so on. The narrative not only explained, but *legitimated* knowledge, and when applied to the social relations of their own society, the myths functioned as a legitimation of existing power relations, customs and so on.

The great religions of the feudal world — Christianity, Islam and Buddhism — institutionalised this narrative knowledge, and monotheism invested the narrative with a unitary extramundane subject as the central agent.

Scientific knowledge is a kind of discourse. As Lyotard observes, for the last few decades the "leading" sciences and technologies have had to deal with language in the form of phonology and theories of linguistics, problems of communication and cybernetics, modern theories of algebra and informatics, computers and their language, etc.

These technological transformations can be expected to have a considerable impact on knowledge – the nature of knowledge cannot survive unchanged. With the arrival of the modern era, natural science introduced a different kind of explanation of things in terms of material processes and causes. Knowledge is and will be produced in order to be sold; it is and will be consumed in order to be valorised in a new production.

Lyotard continues that seemingly science is more subordinated to these prevailing powers than ever before. Can it be the case that *knowledge* and *power* are simply two sides of the same question? Who decides what knowledge is, and who knows what needs to be decided? (Lyotard 1984)

Looked at from a post-modern perspective, *all* knowledge becomes narrative. For example, rather than saying that "the existence of oxygen has been proven", there is a narrative about the experiment that Lavoisier carried out.

The concept of *grand narratives*, and in particular what Lyotard called the "emancipation narrative", concerns the kind of *meta-narrative* that talks, not just about "one damn thing after another", but sees some kind of interconnection between events, an inner connection between events related to one another, a succession of social systems, the gradual development of social conditions, and so on — in other words, it is able in some way to *make sense of* history.

Lyotard's post-modern view of knowledge has far-reaching consequences. It considers one more element that plays a key role when dealing with the question about the availability of reliable knowledge in general or, in the case of studying complex systems in particular. This is the current social and cultural environment, plus the leading kind of discourse. Without these agents into account one cannot speak seriously about any knowledge at all. This represents a new element we can add to the list of difficulties connected with knowing complex – and all other – systems.

Lyotard`s postmodern philosophy has one positive attribute, however: some authors find it inspirational for general complexity studies. One such example is Paul Cilliers, in his book *Complexity & Postmodernism: understanding complex systems* (Cilliers 1998). The reason is that Lyotard stresses the inner connections between the parts of given complex systems and events, and dispensing with the practice of considering things by themselves. This sc. connectionist approach[258] is very promising when

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[258] Connectionism is a method based on the same principles as brain functions. Functionally our brain is composed of neurons that are mutually interconnected by means of synapses. Information proceeds

dealing with complexity, because mutual interconnections and loops of responses are the main characteristics of all complex systems. On the other hand, it is very difficult to grasp any complex system in itself – as we have stated many times in this work. This can be a solution for avoiding these difficulties.

Nevertheless, if we want to keep to the approach of "classical realistic philosophy" it does not help us much. The reason is simple: from this point of view substances – i.e. bearers of action – are the most fundamental subjects of interest, not their manifestations. In other words: if we stick with the brain-analogy, neurons in themselves are the most important things, not their mutual connections or their excitations, even though these things inherently belong to them.

6. Searching for "the why of things"

> Knowledge is the object of our inquiry, and men do not think they know a thing till they have grasped the 'why' of (which is to grasp its primary cause). So clearly we too must do this as regards both coming to be and passing away and every kind of physical change, in order that, knowing their principles, we may try to refer to these principles each of our problems.
> In one sense, then, (1) that out of which a thing comes to be and which persists, is called 'cause', e.g. the bronze of the statue, the silver of the bowl, and the genera of which the bronze and the silver are species.
> In another sense (2) the form or the archetype, i.e. the statement of the essence, and its genera, are called 'causes' (e.g. of the octave the relation of 2:1, and generally number), and the parts in the definition.
> Again (3) the primary source of the change or coming to rest; e.g. the man who gave advice is a cause, the father is cause of the child, and generally what makes, of what is made and what causes the change of what is changed.
> Again (4) in the sense of end or 'that for the sake of which' a thing is done, e.g. health is the cause of walking about. ('Why is he walking about?' we say. 'To be healthy', and, having said that, we think we have assigned the cause.) The same is true also of all the intermediate steps which are brought about

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via routes of neurons that create a brain network. What is important for the movement of information is the network – individual neurons do not matter.

> through the action of something else as a means towards the end, e.g. the reduction of flesh, purging, drugs, or surgical instruments are means towards health. All these things are 'for the sake of' the end, though they differ from one another in that some are activities, others instruments.
>
> This then perhaps exhausts the number of ways in which the term 'cause' is used.
>
> It is clear then that there are causes, and that the number of them is what we have stated. The number is the same as that of the things comprehended under the question 'why'. The 'why' is referred ultimately either (1), in things which do not involve motion, e.g. in mathematics, to the 'what' (to the definition of 'straight line' or 'commensurable', etc.), or (2) to what initiated a motion, e.g. 'why did they go to war?-because there had been a raid'; or (3) we are inquiring 'for the sake of what?'-'that they may rule'; or (4), in the case of things that come into being, we are looking for the matter. The causes, therefore, are these and so many in number.
>
> Now, the causes being four, it is the business of the physicist to know about them all, and if he refers his problems back to all of them, he will assign the 'why' in the way proper to his science-the matter, the form, the mover, 'that for the sake of which'. The last three often coincide; for the 'what' and 'that for the sake of which' are one, while the primary source of motion is the same in species as these (for man generates man), and so too, in general, are all things which cause movement by being themselves moved; and such as are not of this kind are no longer inside the province of physics, for they cause motion not by possessing motion or a source of motion in themselves, but being themselves incapable of motion. Hence there are three branches of study, one of things which are incapable of motion, the second of things in motion, but indestructible, the third of destructible things.
>
> The question 'why', then, is answered by reference to the matter, to the form, and to the primary moving cause. For in respect of coming to be it is mostly in this last way that causes are investigated-'what comes to be after what? ‘what was the primary agent or patient?' and so at each step of the series.[259]

The fabric of reality

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[259] *Physics* by Aristotle, written 350 B.C. translated by R. P. Hardie and R. K. Gaye. http://classics.mit.edu/Aristotle/physics.html

As David Deutsch stresses (Deutsch 1997) there is a significant difference between “to know” and “to understand”. I *know* how old I am, who my mother is, what the capital of Great Britain is, who the president of the United States is, what the water molecule looks like and what the sum of 7 + 8 is. But can I say that I *understand* these things? I cannot. All of them are nothing more than facts that I have learned and that I can present only as statements.

In contrast, to understand implies to be able to *explain*, which is something very different. It is a kind of “knowledge” that goes much deeper, but does not necessarily demand that one know a greater number of facts. It is a matter of understanding of the principles, not summarising lists of data.

David Deutsch gives the following example in his book: one can well understand the principles of the planets’ motion, even it could be beyond human capacity to count every particular movement and trajectory for every planet. Furthermore, we experience many things in our everyday lives where we know how they work in principle, but not all their details. How many of us can describe in detail all of the processes that happen when one starts a car? However, many of us do understand *how* a car works and *why*.

These two approaches to knowledge are complementary and not mutually exclusive. On the contrary, they are strongly interconnected. A general theory can be developed from the lists of measured and counted data with the intention of uncovering a principle, while from the opposite side, knowledge of a principle and theory enables one to get to particular data in every particular situation connected to the given phenomenon.

Since ancient times people have observed that objects on earth always fall down to the ground when dropped. It was understood as a fact that always happened. Nevertheless, to understand *why* it happens took a long time, and the theory of gravity attraction is a relatively new affair.

But by postulating a new theory the whole process does not finish. Afterwards it is necessary – as scientific method demands – to perform a crucial experimental test. This is what Karl Popper stated and elaborated on in his famous book *The Logic of Scientific Discovery* (Popper 1959). Do people, however, test all proposed theories in practice? Of course, not. The proposed theory must look “reasonable” and promising, and also include some *explanation*; otherwise it would a priori be evaluated as “bad”. Naturally, such “bad” theories are not tested.

David Deutsch says in his book (Deutsch 1997: 12) that “‘explanation’ and ‘understanding’ are about *why* not *what*, about the inner working of things, how things really are, what must be so, about laws of nature”. They touch on the innermost matters of things, their nature and their relation to other parts of the world.

A very interesting moment that emerges in this connection – as Deutsch points out – is the fact that “theories sometimes explain even more than we are immediately aware of, and so we can understand more than we are immediately aware that we understand”. It provides space for future progress in understanding the world we live in and brings great optimism. This is not all. It also contains an element of mystery and induces the feeling that there is “*Something*” behind the entire world’s reality that only shows itself accidentally and partly. David Deutsch calls this *the fabric of reality*.

Is the fabric of reality knowable, and how can we know it when we accept the assumption that it is? David Deutsch answers that we can know it only by understanding theories that explain it. If this is true, then it supports the methods of scientific research and scientific efforts in general. This is an attitude that we strongly support as well.

Imagine that we might really understand this “something” – the fabric of reality, as Deutsch calls it. Does this mean that we will understand *everything* at that moment? It is a tricky question, since the word ‘everything’ can be understood in different ways. One can understand it in the sense of *everything there is* or in the sense of grasping the last principle of the universe, enabling one to understand and to predict all things and phenomena that exist and happen in the world.

This idea also puts *the theory of everything* that we discussed in the previous chapter in a completely new light. The theory of everything of the particle physicist, Deutsch says, means the unified theory of all basic forces known to physics, plus knowledge of all the subatomic particles and the initial state, the Big Bang. It is true that this would, in principle, contain all the information necessary to predict everything that can be predicted. However, it does not guarantee an explanation! It stays strictly within the borders set out by a science that is essentially reductionist. But, as Deutsch comments, this is actually not a problem, since no-one expects to deduce all the principles of biology, psychology and politics from those of physics.

People say that it is not possible for an individual to grasp all the knowledge and facts that have been collected by mankind since the beginning of our cognitive and "scientific" life. Even though it might still have been possible for a few well-educated people during, let us say, the Renaissance. There are still people who sentimentally recall those times and regret that they were not born earlier. There is good news for such people. Even though it is probably not really possible for anybody to obtain and keep all known facts, the possibility emerges that it could be possible for an individual to understand the basic principles of the universe, and this to some extent means "to know everything". Although this issue is still rather doubtful, it should not be discarded a priori.

The idea of "the fabric of reality" brings us back to our main topic, i.e. complexity. Why? Because it anticipates the emergence of new qualities, the enormous intricacy of the universe, and the limitation of our knowledge. These are all concerns that are strongly related to complexity and, like these, they were also discussed earlier in this dissertation.

As we have already pointed out, the term 'emergence' is a moot question in itself. It is used in the sense of "emerging" new (read: more complex) qualities at a higher level of the world's hierarchies, but also in the sense of the "emergence" of high-level simplicity from low-level complexity. In accordance with this, one can define emergent phenomena as "high-level phenomena about which there are comprehensible facts that are not simply deducible from lower-level theories" (Deutsch 1997).

This statement is strongly contrary to the theory of reductionism, which proposes that all high-level phenomena are *explainable* from low-level phenomena, and that the former are also reducible to the later. An approach that is quite the opposite is called *holism*, which states that the only legitimate explanations are in terms of higher-level systems. However, it seems that this idea may be an even greater error than reductionism itself.

The fact that inducing predictions from observed data does not work can be illustrated with the help of the well-known story about Russell's chicken. The chicken lived in the yard of the farm belonging to the Russell family and had a very nice life. Twice a day the house-keeper came and gave it (and the others, of course) tasty food. The same happened day after day. Since the chicken was very clever and well aware of possible struggles in life, it doubted every morning whether it would be fed. And it was. After few weeks it lost its fear and became sure that its happy life would last forever. Unfortunately that was a big mistake. One morning the master came, and instead of bringing food for the chicken he took it and carried to the kitchen.

When thinking about this sad story we find that the two possible endings of the story have two different motivations: the lasting care of the chicken would mean the Mr. Russell loves chickens and sees them as pets, while the tragic end means that he only wanted to fatten it up. If the chicken had known the farmer's thoughts, it would have been able to estimate the course of its life correctly.

The result of this consideration is unambiguous: even though we start our process of induction from the same observed data we can get different conclusions depending on the different induction-frameworks.

In his book *The Fabric of Reality: The Science of Parallel Universes – And Its Implications*, David Deutsch gives the following example: Consider one particular copper atom at the tip of the nose of a statue of Sir Winston Churchill. Now the question can be raised: why is that copper atom there?

One can start one's deduction from both sides: from "above", i.e. from Churchill as a person, or from "bellow", i.e. from the copper atom itself. Sir Winston Churchill was - in short - a British politician who was elected as prime minister of Great Britain in 1940. He played a key role in the Second World War's events and after the publication of his six volumes, *The Second World War*, Churchill was awarded the Nobel Prize for Literature. He was without doubt an important person in modern history and because it is customary for people to build statues of such persons, many were made of Churchill, including this particular one we are talking about. A group of people were asked to create this piece and they chose bronze as a suitable material for this. They went to a mine XY and brought the necessary metals from there, including copper. One of the chosen bars contained "our" copper atom, which is now situated at the tip of the nose of the statue.

Coming from the other side we can start the story from the perspective of the copper atom. We can describe its electron configuration and guess at why it found itself in mine XY. Then the question arises: how did it reach the artist's studio, how did it become part of the statue representing Churchill and, finally, who exactly was Sir Winston Churchill?

Just as 'to know' differs from 'to understand' the notion 'knowledge' differs from 'information'. In the foregoing we spoke about 'to know' in the reduced sense of its meaning – as naming data. When we wanted to express some insight into the meaning of these data we used the expression 'to understand'. This distinction is, however, far from being unambiguous, and is rather forced. Normally we use "I know it" when speaking about either quantity or quality. Nevertheless, this distinction helped us to understand the problem we pointed out, i.e. that summarising data is not the same as understanding a principle.

Even more significant is the distinction between the terms 'information' and 'knowledge' (Rescher 1998: 78). By definition, information is expresses by the sequence of 0, 1; it is purely a matter of data. Therefore, the assessment of information is always only quantitative.[260] As quantity, information should be measurable. There is nothing mysterious about it; information is just a quantity.

The situation is, however, much more complicated when we consider knowledge. It is something more select; more issue-resolving. Basic information is something completely different than the insight at issue with actual knowledge.

Nicholas Rescher illustrates this difference with the help of a well-known example: suppose an object-descriptive colour taxonomy reduced to three categories Blue, Red, and Other. Then the single item of *knowledge* represented by "knowing the colour" of an object (for example that it is red) is bound up with many different items of (correct) *information* on the subject (that it is not Blue, is rather similar to some shades of Other, etc.) Any knowable fact, Rescher argues, is always surrounded by a vast cloud of

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[260] Of course, one can speak of"good"and „"bad" information or assign it some creative power, as is popular now-a-days, but it is beyond its first and proper meaning and therefore beyond the line of thinking we want to persue.

relevant information. So we can conclude that *knowledge certainly increases with information, but at a far less than proportional rate*.[261]

Now, if we put the attribute “scientific” in front of the substantives ‘knowledge’ and ‘information’, we can guess that in the same way scientific knowledge won’t correlate with the brute volume of scientific information. But how is one to measure the volume of information generated in the field of science?

Direct methods are hard to come by, but various oblique ways have been suggested; the amount of literature in the given field, for example. It is a familiar fact by now that the printed literature of science has been increasing with an average of some five percent annually throughout the last two centuries (Rescher 1998: 76). It is reliably estimated that about ten million scientific papers have been published thus far, and that currently some 30,000 journals publish some 600,000 new papers each year. In fact, it is readily documented – he continues – that the number of books, journals and journal-papers has been increasing at an exponential rate recently. The amount of scientific material in print is of a scope that puts it beyond the reach of not only individuals but of institutions as well. But what does this say about the *quality* of science and about the *scientific knowledge*?

A few paragraphs ago we said that knowledge is different from information, that it is only *particularly significant information* – information whose significance exceeds some threshold level. Nevertheless, knowledge is strongly dependent on the amount of information. Though this dependence is not trivial[262] it does exist. For we can well suppose that with the increase of scientific information scientific knowledge also increases, and so does the *complexity* of science.

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[261] At this point Rescher stresses that the ‘knowledge’ at issue here need not necessarily be correct: it is merely putative knowledge that represents a comprehensively contrived best estimate of what the truth of the matter actually is.

[262] Some people have even tried to express it exactly with the result that it follows logarithmic dependence.

Finality in nature

Modern cosmological theories generally conceive of the universe as a closed world that explains itself; there is no room for an extra-mundane cause or at least, there is no need for it. The celestial bodies, the earth, the biosphere and man are the result of evolution over long periods of time and not guided by any design (Elders 1997: 135).

But finality does not exclude a certain determinism: it is a fact that chemical elements react according to their nature, or that when the surface of the earth is heated water evaporates, vapour cools off at a certain altitude and water returns in the form of rain or snow. In most cases, however, these predetermined activities lead to a specific goal. This means that this efficient causality is taken up in an encompassing final causality.

> If we want to indicate what the end is of a whole consisting of parts, we note first that the individual parts are for the sake of their own activity, as the eye is for seeing; secondly, that a part of lower standing is for the sake of a nobler part, as the senses are for the sake of the intellect, the lungs for the sake of the heart; in the third place, we say that all the parts are for the sake of the perfection of the whole, as matter is for the sake of the form, since the parts are so to say the matter of the whole; furthermore, the entire man is for some extrinsic end, for instance, to find his happiness in God.[263]

In this text Aquinas states that all things in the world are in the first place for their own perfection; next, that the less than perfect is for the sake of what is more so, continuing to the complete perfection – i.e. God. Here the universe is hierarchically organized: a series of homocentric spheres descend from the outer sphere as far as the lunar region. The world consists of individual substances. Serial chains of causes are finite (*anankè stènai*). The First Mover is the moving and governing power. He is also the ultimate goal of all processes.

This ancient and medieval attitude has, however, long been abandoned. According to modern science, the processes in the world go on forever. The organisation of the world is the result of an evolution in which

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[263] Thomas Aquinas, *S.C.G.* I 65, 2 – quoted according to (Elders 1997: 335).

chance plays a key role. The species of things depend upon the state of the elements, all of which consist of the same “elementary” particles. There are no substances, but only relations between things. The universe is conceived of as a closed world, which explains itself; there is no room for any “external” cause or, at least there is no need for it.

It is obvious that the ancient and medieval conceptions of the universe are erroneous on many points. However, the discoveries of the last decades – especially in quantum physics and complexity studies – indicate that something in them can be good. Especially in that they showed the limits of a merely quantitative approach; a return to the concept of substance and world’s hierarchy seems promising.

Finality does not exclude a certain determinism: it is a fact that chemical elements react according to their nature, or that when the surface of the earth is heated water evaporates, vapour cools off at a certain altitude and water returns in the form of rain or snow. In accordance with this “old” philosophy one could say that it is certainly true, but simultaneously it shows that these predetermined activities always (or in most cases) lead to a specific goal. This means that an efficient causality is taken up in an encompassing final causality, so there is no contradiction at all.

If we return to the very beginning of our dissertation we can recall our statement that complexity requires the openness of a given system and the operation of some external cause on it. For, complexity represents movement towards more perfection; it is a process of the continual originating of something new in the broadest sense of the word. Since “none can give more than he has” some external agent seems to be inevitable. Also, when dealing with things per se, i.e. with ontology, the concept of substances is more than useful. Therefore we conclude that for our purposes this “ancient” and often marginalised (because of its out-datedness) philosophy can be helpful and inspirational.

VII “QUANTUM PIGEON”

We will start this chapter with the question of whether the world is one complex system, or if it consists of different mutually interconnected parts (“smaller worlds”). If the former statement is not true but the latter is, then it would mean that we do not have a choice other than to keep dividing the sciences into individual branches, without any hope for even the theoretical possibility of any synthesis between them. However, if it is not the case then we can imagine the world as a three-dimensional object,[264] which it is possible to approach from arbitrary sites. Thus, if we exaggerate, it should be possible to take some theories and languages developed at one place of this “world-body” and to apply it to something completely different. This is what we would like to test. To realise this experiment we chose a strange couple – part of the theory belonging to quantum mechanics and a pigeon – as an example of a ‘general’ quantum system.[265]

Before we start we will try to summarize what has been said about the ‘structure’ of and ‘knowing’ the world up to now.

The world in itself is a whole composed of different parts[266] with their own boundaries and hierarchically ordered structure.[267] The basic part (unit) of this whole can be represented by many things, depending on one’s interest and distance of observation. It can be an electron, an atom, a stone, a tree, a cell, a man, a society, etc. In classical philosophy this basic unit is identified with the category *substance*. Together with substances accidents are also

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[264] We limit ourselves to three dimensions only, for practical reasons.
[265] Here we kindly ask our readers for generosity with this, at the first glance, absurd attempt.
[266] But not pieces as we pointed out in Chapter II.
[267] These structures are parts of other structures of other structures continuing to infinity.

introduced that play the role of actual characteristics. We observed that complexity itself also belongs to the accidental determinations of a subject.

All substances – or general units – enter into many interrelations with their environment. What is important, however, is the fact that these relations do *not* influence the *nature* of substances.

How do we know the world? This is a very difficult question. One of the possible answers is: through the senses and reason. Through the senses we get to know the *quantity* of a subject, which is changeable. In contrast, through reason we can know the nature of *things*. Only through reason can we recognise them as 'particular things', i.e. substances. Fortunately, it is so well "organised" in the world that accidents can also only change within some fixed limits. In other words, every substance can posses only a certain number of given characteristics. It helps them to keep their own identity.[268]

Now the question arises: how "far" are we able to follow (to monitor) this identity? Naturally, things that are of a similar size as we are and that surround us are closest to us. We are especially familiar with things that we can observe directly, without needing any other tools and which we meet immediately within the course of our lives. Thus, we do not have great trouble in identifying a dog, a house, a narcissus, a pebble or washing machine as different things by their nature. Problems, however, appear when we start to proceed towards things that are too big, or too small or too far, etc. If we leave aside for the moment the last case, i.e. things that are too far from us, as a separate category, we will be left with things that differ significantly from us by their sizes. On the basis of what has been said in the foregoing text, we can, however, also state that at the "ends" of this "world-body" we can presume to find complexity.

Let us imagine the world as a double-cone, similar to the shape of an hourglass (see the following picture). Then, the middle part of the body represents a sphere of the world we live in where the common laws are valid and where we can use our common sense to understand things. This is also

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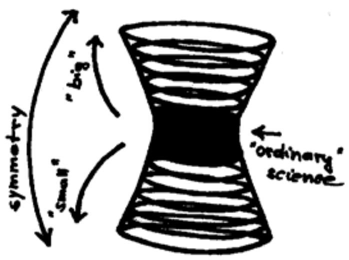
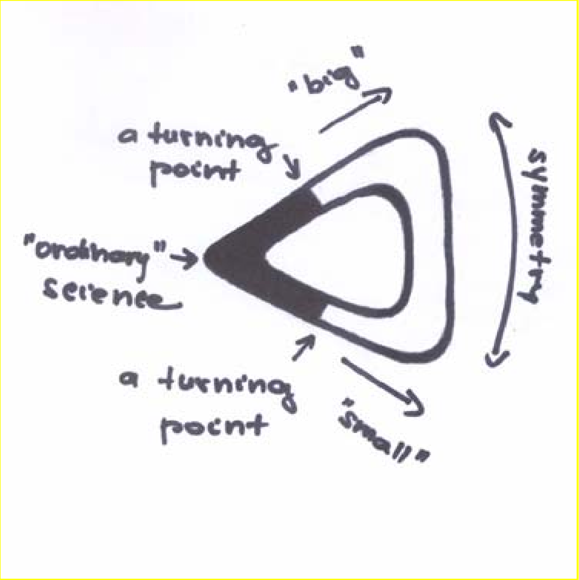
[268] For, if the characteristics of a thing – i.e. accidents – could vary unconditionally then the thing itself would also change significantly, ending in the loss of its own identity. It would cease to exist as *this* thing, *this* substance. And it represents a metamorphosis that is strictly forbidden within the classical Aristotelian-Thomistic philosophy, which we adopted as a starting point for setting the philosophical terminology of our work.

the domain of what we call ordinary science. In this region we successfully apply reductionism, here we can use the method of dividing things into parts when knowing them, and here we can make meaningful predictions. In a word, this is a playground where we can exercise all the common cognitive methods we know.



When we leave this "safe" field and continue "up" we reach the domain of "big" things. These things are so complex that knowing them in detail transcends our abilities. Usually they consist of so many parts that we do not have any chance of recognising all of them and naming them. An even worse situation is with their mutual relationships. They are already so complicated and tangled that any exact description is actually impossible.

One can also find similar conditions at the opposite side of the imaginary double-cone, i.e. in the domain of extremely small things. This area is usually known as the microworld. Here most of our familiar cognitive techniques fail and the results we obtain often do not correspond to our



expectations. The development of some “new” language, suitable to this area is therefore inevitable.[269]

In the picture we tried to depict this situation. “Turning points” represent points where we must radically change our approach to cognition, for we enter the areas that lie beyond direct observation and, among other things, experimental testability. Our imaginary figuration has the shape of an enclosed curve because we suppose that the world is closed and symmetrical. We see complexity as the determination of a sphere that lies above the sphere of simple things and it is also closed and symmetrical. Therefore, it must be approachable from all sides.[270] Moreover, since it is rather homogenous, we can well suppose that results obtained in one part of the imaginary double-cone will be applicable, at least to some extent, in another part. With this thought we have proceeded to the announced theme of the “quantum pigeon”. Let us have a look how it will work...

A pigeon is an example of a living being that possesses a definite identity – it is a univocal substance. It is composed of so many different kinds of parts that nobody can recognise all of them.[271] It develops during the course of its life and interacts strongly with its environment. During life it enters countless relationships, it is endowed with the ability to learn and even with some intelligence. These are some examples of the characteristics that reckon a pigeon among true complex systems.

Now, let’s have a look at some of the parts of quantum-mechanical theory and examine whether they are applicable to “our” pigeon.

- According to J. von Neumann (Neumann 1932) “every process of measurement done on the quantum system contains some ‘unidentifiable element’, which causes that the quantum system undergoes ‘non-continuous, non-causal and sudden’ change in the moment of measurement” (see p. 102).

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[269] The best example of this situation one can be found in quantum mechanics. This is the reason why we have paid so much attention to it and want to continue elaborating on this issue.

[270] That is why we must inevitably clash with it both on the way towards “big” things and “small” things.

[271] It would be impossible to count all of its feathers, and what about its cells, etc.!

What does the pigeon look like when nobody observes it? It is a tricky question that has always troubled philosophers in its many varieties. However, we can honestly acknowledge that we do not know... What does the pigeon look like from a distance? It is already a meaningful question and we can rightly expect that an exhaustive description of some particular bird will follow. It is right but it says something only about the outer appearance of the pigeon and nothing about its inner structure, nature, or “character”. If we would insist on an answer to these next questions then we must either kill the bird (in case we would like to study it from inside) or to catch it and close it in a cage that enables us to observe its behaviour. However, in both these cases (the former one is an extreme) we change the state of the free bird radically and we cut it off from its environment. What is now in our dissecting room or sitting sadly on the perch is definitely “something” different than it was before we started our experiments. Analogically to von Neumann’s statement, we caused a ‘non-continuous, non-causal and sudden’ change on our pigeon.

- One of the fundamental postulates of quantum mechanics states that “before the measurement we cannot say anything about the given system” and all possible answers can be true with the same probability. This situation, however, suddenly changes at the moment of measurement when – by a “jump” – we always get one definite answer to one question.

This consideration takes us back to the previous point. Before we had caught the pigeon and killed it, all options about its innerness and behaviour were equally possible.[272] At the moment of direct observation, however, we “jumped” to certain and definite knowledge.

- According to the theory of decoherence – as formulated by W. Zurek – “the universe is endowed with a great number of non-

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[272] Supposing that we have had no previous experiences with other pigeons that would be transferable to this particular bird.

trivially entangled states and we are capable of holding only an indiscernible part of it. The reason is our finality as observers.”

Although this theory speaks primarily about the mechanism according to which classical reality emerges from the substrate of quantum physics (Zurek 1991) we can forget for the moment about quantum characteristics, and stack “general complex features” in their place. What happens? We can look at a pigeon as if at an object that is itself composed of a great many inner interconnections and enters the same number of relations with its environment. So, how it is possible that we do not see anything other than a huge cluster of these connections but a sharp demarked shape of a particular bird? The reason is the same as Zurek indicated, though in a completely different context: our finality as observers. Since the capability of our “vision” is strongly limited, we see the world as we see it. Nevertheless, one could easily imagine that a more advanced being – let us say God or our Complexity Daemon – can see each reality in its entirety. In Zurek`s words, complex reality “decoheres” into “our” common reality or – from the opposite side – our common reality emerges from the complex substrate due to the effect of decoherence.

- The Many Worlds Theory (MWT) formulated by H. Everett states that there is no difference between the observer, observing device and observed object. All of them can be represented by quantum state vectors. Each experimental situation then corresponds to one state of an observer. It means that the observer actually “sees” everything, but in the particular world – he is finding himself in right now – only one possibility actualises. The rest of them happen in other worlds where the observer is also present but in other “life stories”.

If we again forget about quantum characteristics we can change the theory in the following manner: a complex observer observes a complex object. He sees all its features, qualities, quantities, environmental connections, its history, etc. Each piece of knowledge about this object corresponds to a particular state of the observer. However, each of them realises in a different world. In this particular world we speak about the observer seeing the object as an ordinary pigeon – and what is more, as a quite simple thing. Now, we do not need Complexity Daemons anymore, since we all have the same power and abilities. The only problem is that we cannot take full advantage of it, for we are always kept in just one world, without any possibility of seeing all of them at once.

- Quite similar to MWT is the theory of quantum histories (QH) – see p. 104. According to this theory is that "an infinite number of alternative histories of physical systems exist and all of them are equal in the same manner as the worlds within the MWT". However, the world we experience is again only one. To give a satisfactory explanation one needs some knowledge of a proper physical-mathematical formalism.

A pigeon is certainly not a steady system. It is just the opposite. It changes and develops all its life and in every moment. In every instant the pigeon is somehow different. However, when we observe it, we only see only one "frozen" state each time, without knowing the foregoing past. It can be so that also an infinite number of histories have preceded every fixed-observed state, but we can only decode one of them.

Even though we gave only small hints in the direction of applying some of the theories developed within quantum mechanics to a completely different system – a pigeon – we can conclude that at a very superficial level it makes some sense. Since we have tried to explain the original theories in the chapter devoted to quantum mechanics (V, 6) we have not repeated it in the foregoing paragraphs. We limited ourselves to only a few sentences, cut off from the context, and developed the pigeon story from it. We are well aware of the fact that many physicists will disagree with such a procedure, but we still think that it is at least an imaginative way to approach the problem of complexity.

To continue in this direction and consider more details and to keep to a more rigorous and serious method would acquire a separate work. Most probably one would then clash with the great discrepancy between the two chosen subjects. For, a formalism developed in quantum mechanics can hardly be successfully applied to a pigeon, literally. However, every physical theory consists of two parts: physical-mathematical formalism and its interpretations. And the latter one is exactly what we are the most interested in.

Interpretations are, that is to say, formulated in ordinary words. And any common language – in contrast to mathematical formalism – provides a space for introducing different meanings, which is of crucial importance for the theory of knowledge and of complex systems.[273] The more complicated (complex) the system is, [274] the bigger the need for different interpretations one can see. Thus, it is not by chance that so many of them have been developed within quantum mechanics, since it is a branch of science that deals with tremendously complicated and – from the point of view of our common sense – strange things. That is why we visited precisely this scientific domain when looking for ideas on how to regard complexity in a new way.

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[273] For, as we have stressed many times in the course of this work, it is almost impossible to strictly keep to the unambiguous language of mathematics when talking about complexity.

[274] Regardless of whether it is a complicated quantum system or a complicated living being.

EPILOGUE

In the presented work we pursued the following goals:

- to study the term ‘complexity’ and to gain some knowledge of this phenomenon;
- to categorise complexity and to release it from the cloud of mysticism and fuzziness that usually surrounds it;
- to have a look at where one can come across complexity;
- to disclose the mechanisms of its originating;
- to show a few examples of how complexity is treated in different scientific disciplines, and to show that it makes sense to strive for knowing it as many people have already been doing over the whole world;
- to present some convincing demonstrations that, since complexity is everywhere, it is also approachable from arbitrary sites;
- to develop the idea that the world is one complex system and that all its divisions into different “worlds” – quantum, classical, non-classical, relativistic, complex, etc. – is only artificial;
- to prove the hypothesis that, since the world is symmetrical and homogenous in general, one can also apply theories and languages developed in one of its part to others.

We consider our work as a kind of interdisciplinary study and it should be understood as such. It should be regarded as a *motivational piece* and not as an exhaustive study done on the particular theme. It belongs to one of the main goals of our efforts to underline the importance of *interdisciplinary work*, stressing the need of a dialogue led between the sc. exact sciences, the sc. applied sciences, philosophy and between the individual scientific branches as. We hope that we have at least partly succeeded to show that, although this kind of work is very hard, it is also exciting and promising.

Moreover, we are strongly convinced that such interdisciplinary work is inevitable for any further progress in knowing the world we live in and even for knowing ourselves. Despite the fact that the contemporary trend looks to be the opposite – leading to narrow specialisation – the need for interdisciplinary theorists is not weaker, but even stronger. Without people who are able to generalise things, to put them together, and to watch them as if from above, there would be no true progress at all. For they show new ways going further and give feedback.

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