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The Knowledge of Complexity should be a part of Contemporary Education

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Abstract

In order to be prepared to face the challenges of the global world, contemporary education should include the knowledge about the complexity of the world. The basis for understanding complexity is to recognize that everything around us is made of interconnected and interdependent elements (individuals, pieces) depending on the scale. In general, it is impossible to predict the properties of a system by simply summarizing the properties of single elements. The interrelations promote and inhibit the properties of and changes in systems. In this paper the complexity of physical systems is briefly described and then attention is turned to complex thinking. The basic knowledge about complex systems has revealed many essential properties: the importance of simple but repetitive rules, the importance of non-linearities, sensitivity to initial conditions, the possibility of self-organisation, the existence of networks, etc. There are many simple and brilliant examples which illustrate the behaviour of complex systems like small world, sand piles, the butterfly effect, birds in flight, emergence of chaotic motion, etc. that do not need complicated mathematics but demonstrate the richness of the world in unexpected ways. It is argued that contemporary education should include descriptions of such simple models which form a set of cornerstones for understanding more complicated phenomena and functioning of the world. The educators should pay more attention to primers in complexity for preparing pupils not only along traditional fragmented disciplines but also generalizations. This will help next generations to manage future challenges.

We need to deeply reform all our ways of knowing and thinking

– Edgar Morin (2006)

1. Introduction

The World around us is complex which in a nutshell means that it cannot be understood only by analyzing its constituents whatever they are, physical entities or living organisms. The notion "*complexus*" itself means what is woven together and this togetherness makes the world not only richer but much more interesting. During the last half century much attention is paid to analyzing complex systems including the physical, biological, societal phenomena and explaining the ideas of complexity from the philosophical viewpoint. Sometimes the notion "complexity science" is used. According to Roger Lewin (1993), "*Complexity science offers a way of going beyond the limits of reductionism, because it understands that much of the world is not machine-like and comprehensible through a cataloging of its parts; but consists instead mostly organic and holistic systems that are difficult to comprehend by traditional scientific analysis".* An extremely important question is how these understandings are reflected in the educational system.

In this paper a brief explanation is given about the importance of complex systems together with ideas as to how the knowledge on complex systems could be introduced to educational system(s). In Section 2 general principles of complexity in physical systems are described which form a good basis for understanding complexity. Next, in Section 3, philosophical questions related to complex thinking are briefly analyzed. Section 4 includes some ideas about education of complex systems. General conclusions are presented in Section 5.

2. Complexity as understood in physics

Classical research aims to split up general problems into their simpler components and then to study them as deeply as possible. An extremely impressive explanation is given by Alvin Toffler (1984): "*One of the most highly developed skills in contemporary Western civilization is dissection: the split-up of problems into their smallest possible components. We are good at it. So good, we often forget to put the pieces back together again."* Such an understanding is changed in the scientific world although in everyday life, the simplifications as Toffler has warned, are still widely used.

The essence of complexity in physical systems is described in many monographs (Nicolis and Nicolis, 2007; Érdi, 2008; etc.) and for the encyclopaedic overview one should consult the "Encyclopaedia of Non-linear Science" (Scott, 2005). What follows is a brief survey of main effects which are important for understanding complexity (Weiler and Engelbrecht, 2013):

i. non-additivity and non-linear interactions. This is the source of chaotic motions and typical of many physical systems modelled by mappings or differential equations. A typical example of a non-linear interaction is the gravitational force between different masses. The three-body system (Sun, Earth, Moon) analyzed by H. Poincaré already more than a century ago has revealed ideas of possible instabilities. Another iconic example is the Lorenz attractor describing simplified atmospheric motion using the system of three non-linear differential equations.

ii. deterministic unpredictability. The behaviour of deterministic non-linear systems may not be predicted and lead to the *chaotic regimes* of motion. A typical example is a simple logistic equation (mapping) derived for calculation of changes in the number of species. The weather is described by the non-linear Navier-Stokes equations that again do not permit accurate forecasts for longer periods.

iii. sensitivity to initial conditions. Small changes in initial conditions for a dynamic non-linear process may lead to large changes in resulting quantities in the course of time. This phenomenon within the framework of a non-linear simple model was discovered by Lorenz although Maxwell already hinted to such a possibility in the 19th century and Poincaré, in the beginning of the 20th century. As far as the accuracy of physical quantities is limited in their value, there exists a so-called *predictability horizon* (Lighthill, 1986) because for example one simply cannot determine the temperature distributions needed for long-term weather forecasts with the accuracy of many digits after comma.

iv. there are several typical phenomena characterizing the behaviour of non-linear systems like *bifurcations* when the new solutions emerge after small changes of control parameters, *emergence* when new patterns arise at the system level not predicted by fundamental proprieties of the system's constituents; *attractors* where the solutions are attracted to a certain space of variables (phase space), *multiple equilibria* which are characterized by several (co-existing) attractors, *thresholds* which mark the borders between the various states, *coherent states* where effects are balanced, *adaptability* when independent constituents interact changing their behaviors in reaction to those of others, and adapting to a changing environment; *self-organizing criticality* when a complex system may possess a self-organizing attractor state that has an inherent potential for abrupt transitions of a wide range of intensities while the magnitude of the next transition is unpredictable, phase transitions, etc.

v. despite the variety of chaotic motions, there are several rules which govern the processes (see Scott, 2005): period doubling and Feigenbaum numbers, power laws, self-similarity, fractality of attractors, etc. and also a number of methods which allow analysis of the processes: Melnikov method, renormalization method, determination of the Kolmogorov entropy and Lyapunov exponents for determining the scale of chaotic motions, etc.

Next, from phenomena and properties one should turn their attention to structures. The main structural cornerstones of a complex world and processes are *fractals, networks*, and *hierarchies*. A brief but sufficient description of these structures is given by Engelbrecht (2016) and here we follow this description. The word "fractal" was coined by B. B. Mandelbrot (1975) using the Latin *"frāctus"* (broken or fractured) for describing irregular non-differentiable structures. The famous Mandelbrot fractal is generated by a quadratic mapping in the complex plane and possesses a wonderful property—self-similarity. In simple words, under various degrees of amplification (zooming), each small part of this fractal replicates the structure of the whole. It means that such objects are scale-invariant and in addition are characterized by non-integer (fractional) dimensions. The fractal geometry (Peitgen et al., 1992) is based on the idea of using feedback procedures that are simple repetitive rules for constructing very complicated structures. The iconic fractals named after Mandelbrot, Koch, Sierpinski, Cantor, Barnsley, etc. display explicitly the properties of fractals. The fields of using fractals for describing physical phenomena cover a wide area of nature and technology: from coastlines to crystals, from describing attractors in phase spaces to Brownian motion, from fractals in biology to structures of time-series of financial markets, from characteristics of seismic activity to music, from mountain ranges and structure of lightning to heart rate, etc.

The lesson to be remembered is that the repetitive usage of simple rules generates complicated objects which possess some universal rules.

Another important notion is networks. In simple words, a network is formed by a large set of elements (nodes) which are connected through a pattern of different interactions (links). The world is full of networks: the ecosystems form networks and webs of species, our computers are linked to the Internet or connected to cloud computing, the public transportation system forms a network starting from local connections to intercontinental flights, economics and electric grids form a global network, social networks unite persons, etc. Again, there are several universal rules which help to understand life in global networks (Barabasi and Frangos, 2014; Caldarelli and Catanzaro, 2015). A powerful tool for describing networks is the graph theory which started with the problem of crossing Königsberg's bridges. L. Euler showed in the 18th century that given the number of bridges, it is impossible to walk over all the 7 bridges only once. Nowadays we know much more about the structure and behaviour of networks. Despite the large number of nodes and links, a small world phenomenon exists with only six degrees of separation. Networks are in general terms stable and large networks do not usually break under the failure of one node or link but in some cases domino effects and cascading failures occur. The cases of failure of electric grids are known as warning examples with large-scale effects. The power law governs the network structure but not as an ideal rule because in reality the power-law might have "fat tails". There are certain limits in networks, in social systems for example, the Dunbar number (which is estimated around 150) limits the number of possible active social relations. The Matthew effect (the rich get richer) seems to be important not only in economics but also in science where attention is given preferably to known names (to Nobelists, for example).

An important notion in the analysis of physical systems is related to scales. Just remember the large-scale structure of the Universe and the nanoscales in contemporary technology. That is why hierarchies are of importance. The general definition says that a hierarchy is an organizational structure where the constituents are ranked according to some principle: the level of importance, scale or other properties. Usually related to social systems, hierarchies are also used for the modelling of physical systems, where processes at different levels having different scales are described by different models (equations) which are coupled into the general system (Engelbrecht, 2015).

To sum up, complex physical systems are pretty well described but intensive studies are in progress.

3. Complex thinking

Society is a complex social system. In terms of notions described in Section 2 for physical systems social systems can also be modelled by networks and clusters, communities and alliances and are spatially and temporally differentiated. Society is able to function not only because of its structures but the behaviour of its members (constituents is physical sense) and links (interactions in physical sense) between them play the most important role. Turning to complexity of physical systems (Section 2), the interactions between the constituents are described by physical laws that can be measured at least with certain accuracy. In complex social systems the situation is much more complicated because the links are based on accepted rules (laws), traditions, language, and governance, on economic and environmental conditions and certainly on values. The basic question in social systems is how the members of the society (humans) actually understand and interpret societal problems. According to Scott Page (2010), "*...physical and computational measures of complexity exist in abundance. These can provide a starting point for creating social complexity metrics, but they need refinement for the simple reason that electrons don't think"*.

Indeed, philosophy needs to introduce "complex thinking". Such thinking owes much to the French philosopher Edgar Morin who has studied complexity from an epistemological viewpoint (see for example, Morin, 2007; also Morin, 2006). The main ideas of Morin are described in a monumental collection of his studies in 6 volumes (Morin, 1977-2004).

As stated in the Didactic Encyclopedia (2015), complex thought "*refers to the ability to interconnect different dimensions of reality. ... Complex thought is therefore a strategy or a way of thinking which intends holistic phenomena but which, at the same time recognises the specificity of the parties. ... Everything that concerns complex thinking is related to epistemology"*. Many scholars have followed the ideas of Morin (Schlindwein and Ison, 2004; Ferrera, 2010; Loubser, 2014; Malaina, 2015; etc.). Morin himself has summarized his idea in a brilliant paper (Morin, 2006) as follows. Classical science has rejected complexity because of three principles followed in research: universal determinism (Laplace's Daemon), reduction and disjunction. However, note that Morin does not mention the early ideas of oriental thinking. The importance of the second law of thermodynamics is stressed which means irreversibility of processes. Then quite logically, the problems of order, disorder and organization appeared and needed more attention because of the possible emergence of new systems which could also involve chaos. Now Morin makes a distinction between restricted and general complexities. He calls as "restricted complexity" all these results of research on the complexity of physical systems described above in Section 2 involving chaos theory, unpredictability, fractal concepts, etc. As a philosopher, Morin is keen to speak in terms of "general complexity" and thinks of complexity epistemologically. These two notions are actually the sides of the same coin and both sides need to be studied. I do not agree with Morin that "restricted complexity" is limited and still remains within the epistemology of classical science (Morin, 2006, p6) and the paradigm of classical science is only "fissured", i.e. cracked. I agree that complexity questions in "restricted complexity" are not studied with such philosophical deepness but the general mindset of scientists has clearly changed over the last few decades. Contrary to Mori's thought (2006, p21), complexity as it is understood nowadays by many is related not only to physical sciences or biology (i.e. to restricted complexity) but concerns also human beings, individuals, societal groups, etc. Some examples are given by Weiler and Engelbrecht (2013) concerning policymakers, economists etc.

Certainly, the well-known maxim "*the whole is greater than the sum of its parts*" (attributed to Aristotle) serves the understandings of the society well. Morin adds that the whole is less than the sum of its parts. Indeed, "*a certain number of qualities and properties in the parts can be inhibited by the organization of the whole*". He himself cites Pascal: "*one cannot know the parts if the whole is not known, but one cannot know the whole if the parts are not known*". And then Morin comes to the hologrammic principle: "*not only a part is inside a whole but also the whole is inside the part*". He stresses the importance of feedback, relations between local and global, and what is very important—the link between science and philosophy. Morin has strongly advocated that we have to raise the concept of system (and complexity) from the theoretical level to the *paradigmatic level.*

The philosophical framework for understanding complex systems was intensively studied also by Paul Cilliers (1998). It is interesting to follow his characteristics of complex systems compared to physical explanations (see Section 2). Cilliers (1998, pp 3-5) offers the following list: (i) complex systems consist of a large number of elements; (ii) a large number of elements are necessary but not sufficient; interactions can be either physical or the transference of information; (iii) the interaction is fairly rich; (iv) the interactions are non-linear and non-linearity guarantees that small causes can have large results, and vice versa; (v) the interactions usually have a fairly short range; (vi) there are loops in the interactions (feedback); (vii) complex systems are usually open systems; (viii) complex systems operate under conditions far from equilibrium; (ix) complex systems have a history; (x) each element in the system is ignorant of the behaviour of the system as a whole; complexity is the result of a rich interaction of simple elements. He uses these characteristics later for describing economic systems. Then Cilliers comes to the storing of information and the development of the internal structure, i.e. self-organisation. The next natural step in describing complexity is modelling where Cilliers distinguishes rule-based and connectionist models. Much attention is devoted to self-organisation and his definition grasps all the needed qualities: "*The capacity for self-organisation is a property of complex systems which enables them to develop or change internal structure spontaneously and adoptively in order to cope with, or manipulate, their environment*". Finally Cilliers comes to the postmodern society describing it as a complex system using the characteristics listed above. Later (Cilliers, 2001) turns his attention to boundaries, hierarchies and networks in complex systems.

Comparing the characteristics of complex systems listed in Section 2 (issues (i)-(v)) and above (issues (i)-(x)) it can be concluded that in physical systems much attention is based on phenomena which could take place in complex systems and to possible quantification of those phenomena. If we follow Cilliers in his philosophical presentation then the attention is on interactions. An excellent analysis of such an approach is made by Spurrett (1999). He points out that Cilliers (1998) claims that "*chaos theory, and especially the notion of deterministic chaos and universality, does not really help us to understand the dynamics of complex systems*". This is based on Cilliers' understanding that model cases of chaos are based on comparatively small number of elements (degrees of freedom) while usually complex systems have a large number of elements. Like Spurrett, I cannot agree with this statement. Physical modelling can start from a huge number of elements all described by their governing equations. The usual way is to transfer these models to the continuum approach and the final governing equations are then partial differential equations. Such an approach helps us to understand predictability and determinism in large systems (cf weather forecast). Cilliers also mentions ethics in complex systems (Cilliers, 1998, p 136-140) but in my view, although extremely important, this problem will need much more studies rather than arguing about leading principles in complex systems. One can certainly agree with the philosophy of "*Respecting otherness and difference as values themselves*".

Actually Knyazeva (2004) explains the philosophical sense of the concept of non-linearity which is crucial to complex systems. She states that evolution in a non-linear system includes (i) the idea of multiplicity of evolutionary paths; (ii) the idea of choice between these paths; (iii) the idea of tempo of evolution; (iv) the idea of irreversibility of evolution. In this way she demonstrates by several examples that complexity is really a multi-faceted phenomenon in the universe and formulates the principles of complex non-linear thinking. It is worthwhile to list these principles: (i) the constructive role of chaos in evolution; (ii) the elements of pre-determination in the field of multiple evolutionary paths, (iii) the laws of very fast, avalanche-like processes in complex systems; (iv) the existence in changing rhythms and regimes of evolutionary processes; (v) the patterns of constructing complex totalities from simpler elements. Based on these understandings of evolution and self-organization, Knyazeva (2004) formulates the principles of soft management of non-linear complex systems. The self-control and evolutionary prohibition rules together with topologically correctly organized perturbations upon complex systems are the keywords for the system to be developed in an appropriate way. In this Knyazeva (2004) shows the way how knowledge on complex systems can lead to applications.

Clearly understanding from the physical fields of science which explain phenomena and from philosophy which explains senses are mutually illuminating.

4. On Education

The present understandings as briefly described above very clearly demonstrate complexity and globalization of the world. In order to be prepared to face the challenges of the fast changing global world, contemporary education should also include knowledge about the complexity of the world. Actually one should distinguish two main issues in education: first, education is a complex system itself and second, disseminating knowledge about complex systems.

In general terms, the ideas of changes in educational curricula are collected in a UNESCO paper (Morin, 1999). Among other proposals a major problem is underlined as to "*how we can encourage a way of learning that is able to grasp general, fundamental problems and insert partial, circumscribed knowledge within them*." It is also stressed that "*we should teach methods of grasping mutual relations and reciprocal influences between parts and the whole of the complex world*". This means clearly the changes in the educational system itself. Applying ideas of complex systems in education lead to many implications (Jacobson and Wilensky, 2006). These implications include cognitive issues, curricular contents, pedagogical research on learning complex systems ideas, etc. It looks like we have recognised education as a complex system (Jörg et al., 2007).

Leaving this important issue about restructuring the science of learning as a complex system, let us discuss the second issue—how to disseminate knowledge about complex systems.

In principle, there are two possibilities to introduce new knowledge: either to start from a very general knowledge within the framework of philosophical thinking and then move on to examples or to start from simple examples and then move on to philosophical generalisations. I strongly support gaining knowledge from simple examples which include nowadays brilliant, even iconic cases related to everyday life.

At the level of beginners or at the primary level of education, the descriptions of examples cannot use sophisticated mathematics. In what follows, several examples or problems are described which could form a basis for teaching complex systems in secondary schools. Actually even the solution of a usual quadratic equation could serve as a step for raising the problem of multiple solutions.

The first example is based on building a simple sequence of numbers

$$x_0, x_1, x_2, x_3, \ldots, x_n, x_{n+1}, \ldots .$$

Let us assume that every $x_{n+1} = f(x_n)$ which means that for given function $f(x_n)$ and knowing x_n we can calculate x_{n+1}. Let now

$$f(x_n) = \lambda x_n (1 - x_n),$$

where λ is a constant. Such a simple non-linear model is used for predicting the growth of populations. It has remarkable properties—depending on the value of λ it can describe a chaotic regime. In other words, the number of members of a population cannot be predicted. This model, called the logistic equation is an iconic model of chaos, describes bifurcations (abrupt changes of the character of the sequence), periodic doubling (repeating the same sequence after 2, 4, 8 with different values), emergence of chaos starting from $\lambda > 3.569945...$, self-similarity (repeating the same sequence at a different scale), etc. Much can be studied from this example (see for example, Peitgen et al., 1992) including the universality in chaotic regimes.

Next example: how to construct a snowflake. Take a simple triangle as basis and divide each side into three parts, then remove the central part and build a smaller triangle to close the gap. Repeat such a procedure n times and you get a snowflake called after the Swedish mathematician H. van Koch. This might be the first introduction to fractals (see also Section 2). The famous Mandelbrot fractal needs a little bit more complicated rules (Mandelbrot, 1975) to be followed but the resulting "gingerbread man" has opened the eyes of many researchers about the richness of fractals for their self-similarity properties. Methods for constructing different fractals are given by Peitgen et al. (1992). They have proposed simple algorithms called deterministic iterated function systems (IFS), which function as a "machine". The ISF needs an input image, several lenses which reduce the input image by setting a reduction factor and then a configuration of lens for the assembly of copies. Again, like for the Koch snowflake, the procedures must be repeated, so the feedback idea is used. The results are marvellous fractals including Barnsley fern, Cantor maze, dragons, etc. Here the programming skills are useful but this is not the problem in schools. An interesting problem related to fractality is measuring the length of the coastlines which besides its practical importance also has certain cognitive value.

Then let us discuss how to build a sand-pile (Bak, 1997). Just let sand flow from your palm to a flat surface. A pile will be formed and the more sand you add, the steeper the pile becomes. Then avalanches start to slide down the pile surface and an interesting problem is to guess where the next avalanche starts and whether it reaches the flat surface. It is not an easy task but Bak (1997) was able to find some regularities and patterns in this, let us say such "childish" problems are useful for predicting earthquakes, landslides, traffic jams, etc. Used as a metaphor, this example is rather useful to demonstrate that the laws of physics are simple but nature is complex.

Finally, one more simple example—let us look at the flocking of birds (Reynolds, 1987). This is a paradigmatic example of self-organised collective behaviour. The rules governing a flock and keeping a distance from neighbours are simple indeed: (i) separation—avoid crowding neighbours meaning a short range repulsion; (ii) alignment—steer towards the average heading of neighbours; (iii) steer towards the average position (centre of mass) of neighbours meaning the long range attraction. Again, the skill of programming helps to model such behaviour but is easily realisable. This model explains not only the flocking behaviour of birds but also the shoaling behaviour of fish, the swarming behaviour of insects, and the herd behaviour of land animals. The beautiful images of flocks and swarms could certainly raise the interest to such complex behaviour. The flock-like behaviour of humans when drawn to a focal point (entrance or exit) or escaping (from gunfire) can also be modelled similarly. Even physics of condensed matter can use the results of this analysis.

The list of simple examples is certainly longer and depends on the level of students. The goal of education should be introducing such simple notions into curricula in order to prepare pupils' mindset for more complicated analysis. Advanced level graduate courses, besides more complicated examples, should also involve techniques for analysis (Nicolis and Nicolis, 2007; Érdi, 2008; Scott, 2005). The modelling is based on differential equations and mappings and the space of state variables is sometimes more informative than the usual time-series. The analysis involves stability of solutions, constructing the power spectrum for solutions, reducing the very high-dimensional systems to systems with a smaller degree of freedom, scenarios for the onset of chaos, emergence of patterns and ensembles in nature, etc. The list of applications is extremely long: weather predictions, percolations, heart dynamics, mechanisms of turbulence, phase transitions, forest fires, cellular growth, economy and much more, even music. These applications demonstrate not only the utility and transdisciplinarity but also the beauty of the complexity of world. From the description of complexity in physical systems (Section 2), an important property of non-linear systems should be stressed once more—sensitivity to small changes in initial conditions. Either used in its direct way or as a metaphor, this property has many consequences even without mathematical models.

With such knowledge on non-linear complex systems, further courses on complex thinking could generalize the understanding in all fields of human activities, especially social systems. This should also be a part of contemporary education. However, introducing examples of non-linear complex systems, one should be aware of difficulties in the teaching process (Jacobson and Wilensky, 2006), like problems of inappropriate proportional reasoning, randomness-determinism confusion, anticipation of emergence of new structures, etc. The ideas of improving science education in general have already been flourishing for some time. For example, Lederman (2001) calls for restructuring curricula in high schools. He notes also difficulties like the willingness of teachers to change what and how they teach, the willingness of institutions to change their policy, etc. And certainly it means also increased costs of teaching because of training the teachers, preparing new curricula, preparing and publishing new materials, etc. The leading motto of changes could be along Lederman (2001) "*to marry the physical and biological universes with the wisdom of humanities and with the essential creativity of art, music, and literature*".

5. Final remarks

In the report of LERU on future universities (Boulton and Lucas, 2008), it is said that universities should develop "*the thinking and the mental and conceptual skills and habits that equip their graduates to adapt to change and even steer it if circumstances permit*". That is why we have to teach about the complexity of the world and how it is related to numerous problems: climate change, economy, energy, agriculture, policy, etc. (see Weiler and Engelbrecht, 2013). Examples of application include the analysis of predictability in policymaking (OECD, 2009), economic complexity (Caldarelli et al., 2012), network analysis (Barabasi and Frangos, 2014), etc.

The courses on complexity are often based on courses on non-linear dynamics and are in the curricula of many universities. This experience should be used more widely. However, educators should pay more attention to primers in complexity for preparing pupils in schools not only in traditional fragmented disciplines but also in generalizations. This will help next generations to manage future challenges. An excellent example is the publication series of the Publishing House POLE for disseminating knowledge on mathematics (see Initiation aux Systèmes Dynamiques, 1998). And certainly, the teaching of complex phenomena and methods for their analysis should be united with complex thinking. Educated, competent people can influence societal changes through their action and messages by combining knowledge from unrelated disciplines and their expertise. It is a challenge to create the holistic mindset for future generations.

The monumental collection of ideas on complexity is presented by Meyers (2009) but one should also add the philosophical analysis of complexity (Hooker, 2011). Hopefully soon we could add the overview on complexity in education.

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