Complexity in Social Systems and Academies

Complexity in Social Systems and Academies

By

Jüri Engelbrecht

Cambridge Scholars
Publishing

Complexity in Social Systems and Academies

By Jüri Engelbrecht

This book first published 2021

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-7309-5
ISBN (13): 978-1-5275-7309-3

CONTENTS

Part I Complex systems

1. Phenomena in complex systems

2. Functionality

3. Education

4. Complexity in modelling

Part II Academies

5. Academies are united

6. Actions in academies

7. Knowledge management

PREFACE

The essays collected in this volume are devoted to the phenomena of complexity and academies. Both topics stem from the author's activities. On the one hand, complexity studies are related to the author's research over a long period of time, and on the other hand, the author has been active in academies for three decades. The usage of the plural 'academies' means activities nationally (the Estonian Academy of Sciences) and internationally (ALLEA, WAAS, etc.). The essays reflect my thoughts over the last period (about 10 years) and have been published before in various journals and magazines.

However, collecting these essays under one cover means in a nutshell that this is an attempt to present general ideas on the complexity of physical and social systems within a general framework demonstrating various applications and the main actors. Such a presentation could improve the knowledge of these complexities among the wider community. The technical details are left aside, except for one example included to demonstrate the author's research in wave motion. It follows that one should pay attention to the growing importance of interdisciplinarity and transdisciplinarity, which leads us directly to academies. By definition, academies unite top scientists and scholars representing all fields of knowledge and are in this way the best advocates for the management of general ideas.

The author's background is in mathematical physics, more specifically nonlinear dynamics and biophysics paying attention to nonlinear interactions and the emergence of wave ensembles like soliton trains. The author's monographs on these topics reflected the complexity and simplicity of nonlinear wave motion [1] and general ideas on modelling waves [2]. These studies were joined later by works on the more general problems of complexity science, like those shown in B. Castellani's Map of the Complexity Sciences [3]. As mentioned above, the other pillar in the author's activities is related to academies and the policy of science. Earlier thoughts on these experiences are reflected in two collections [4, 5] - the first on the experience in the Estonian Academy of Sciences, the second on the experience at the international arena in the European Federation of National Academies of Sciences and Humanities (ALLEA).

This volume is divided into two parts. Part I deals with general problems of complexity. It starts with the description of the general ideas of complexity written together with Raoul Weiler (1938-2019) to generate discussions in the World Academy of Art and Science (WAAS). Many of the following essays are based on talks at conferences organised by the Montenegrin Academy of Sciences and Arts in Podgorica. From the viewpoint of the author, the essential argument in Part I is on the values of the complex society. Namely, it is claimed that in societal systems values are the leading and guiding factors, just as thermodynamical constraints are in physical systems. The similarities and differences between physical and societal systems are analysed in several essays. It is stated that the knowledge of complexity should be a part of contemporary education. Based on the knowledge of complexity, the global problems of prediction and the limits of technology and knowledge are discussed. The final essay in this section reflects directly the author's studies in dynamics within the framework of complexity – the only technical paper in this collection.

Part II deals with the activities of academies in the present information-rich complex society, and the author intends to demonstrate that academies are strong actors in applying the ideas of complexity. The opening essay reflects the brief history of academies up to the present time. Then the way in which ALLEA unites the ideas and activities of European National Academies and how academies influence general science policy are described. A couple of addresses for the anniversaries of academies are also included to stress the development of knowledge within one country and over its borders. This means the synergy between the national initiatives is spread into much larger actions. The values generated by academies are stressed, which is again a strong link to general societal problems (Part I). The last essays reflect the present situation and current tasks of academies in society. Conclusions as to what this is all about are presented in a Summary.

No man is an island entire of itself, said John Donne in 1624. The views of the author have been developed by research in the Institute of Cybernetics (formerly at the Estonian Academy of Sciences, later within Tallinn University of Technology) since 1969. The role of the Centre for Nonlinear Studies – CENS (1999-2015) launched by the author for the analysis of complex physical problems has been essential for further generalisations [6]. Thanks go first to all the close colleagues in CENS and also to colleagues from other countries: Manfred Braun, Franco Pastrone, Andras

Szekeres, and certainly to the late Gérard Maugin (1944-2016) for fruitful discussions on the understanding of nonlinear science. It has been a privilege to be part of the activities of academies, especially those within ALLEA, and to collect thoughts about the functioning of the society together with ideas for the future. Discussions with many colleagues – Nicholas Mann, Ivo Šlaus, and Nikolai Alumäe, just to name a few – have greatly helped to understand the societal problems and formulate the ideas. The initiatives of the Montenegrin Academy of Sciences and Arts and WAAS are greatly appreciated for organising meetings. Thanks to my co-authors Raoul Weiler, Momir Djurovic, and Thomas Reuter for the fruitful cooperation. Kert Tamm and Tanel Peets have read the manuscript, making corrections for which I am grateful. I also acknowledge the excellent help from Laurence Fenton on the style and English grammar of the manuscript. Finally, thanks to all the institutions and journals who permitted the reprint of essays published earlier under their auspices.

Special thanks to Cambridge Scholars Publishers and Adam Rummens for publishing this collection of essays.

Jüri Engelbrecht
December 2020

References

[1] J. Engelbrecht, *Nonlinear Wave Dynamics. Complexity and Simplicity*. Kluwer, Dordrecht, 1997.

[2] J. Engelbrecht, *Questions About Elastic Waves.* Springer, Cham et al., 2015.

[3] B. Castellani, Map of the Complexity Sciences. Art & Science Factory. https://www.art-sciencefactory.com/complexity-map_feb09.html (Accessed Nov. 15, 2020)

[4] J. Engelbrecht, *Attractors of Thoughts*. Estonian Academy of Sciences, Tallinn, 2004.

[5] J. Engelbrecht and N. Mann, *The Sum of the Parts: ALLEA and Academies.* ALLEA, Amsterdam, 2011.

[6] J. Engelbrecht *Complexity in Engineering and Natural Sciences and Centre for Nonlinear Studies – Overview of studies 1999-2015.* 86 pp.

Research Report 317/16, Institute of Cybernetics at Tallinn University of Technology, 2016.

ACKNOWLEDGEMENTS

The author is grateful to the following organisations and publishers for granting him their kind permission to republish papers or the texts of talks and addresses:

World Academy of Art and Science – WAAS;
All European Academies – ALLEA;
Montenegrin Academy of Sciences and Arts;
Croatian Academy of Sciences and Arts;
Israel Academy of Sciences and Humanities;
Estonian Academy of Sciences;
Estonian Ministry for Education and Research.

The corresponding bibliographic data are shown in every essay or address.

PART I

COMPLEX SYSTEMS

1. PHENOMENA IN COMPLEX SYSTEMS

1.1 NETWORKS AND COMPLEXITY

This essay first appeared as “The new sciences of networks & complexity: a short introduction”. Cadmus, 2013, vol. 2, issue 1, pp. 131-141, co-author R. Weiler (reproduced here with the kind permission of WAAS).

Preamble & Frame

Networks and complexity have been recognised for quite a few decades. Nevertheless, in recent years real breakthroughs have taken place in particular with the help of new mathematical instruments. However, other ‘new sciences’ have also emerged in the last fifty years, as explained by John Curry in his overview on complexity [1]. The studies on complexity were collected within an extremely comprehensive diagram that is presented in the book by B. Castellani and F. Hafferty “Sociology and Complexity Science. A New Field of Inquiry” [2]. This diagram is nowadays called Castellani’s Map of the Complexity Sciences. It will be a helping hand for setting up the present paper and is further highly recommended to be consulted. A multitude of new knowledge ‘providers’ have shown new ways and insights for exploring entities, ensembles, and the behaviour of groups in very different domains. According to the diagram, several new sciences have emerged since the middle of the twentieth century: the essential pillars for these new ideas are Systems Theory [3], Cybernetics [4], and Artificial Intelligence; from there on a series of specific approaches emerge.

Cybernetics plays a central role in the development of the acquisition of new or additional knowledge. A useful definition of cybernetics is taken from Merriam-Webster [4]:

> “Cybernetics is the science of communication and control theory that is concerned especially with the comparative study of automatic control systems (such as the nervous system and brain and mechanical-electrical communication systems).”

According to the diagram [2], Complexity Science was preceded and followed directly or paralleled by a series of new methods and approaches, such as Self-Organisation/Autopoiesis, Network Science, and the Global

Network Society. Not to forget the importance of the Dynamics of Systems Theory, in which Jay Forester of MIT occupies a major role, and which led to the publication of the first report to the Club of Rome: “The Limits to Growth” [5].

We all agree that our societies evolve to more complex entities; it is seen in economic globalisation, planetary communications (wired and wireless), geopolitical conflicts, and the like. However, the decision processes at the political and societal levels continue to rely on habits and practices from ancient times: the ‘rule of thumb’ is often still the method used in decision processes. The linear analysis in decision processes remains the most used approach in management and governance questions, although we are aware of the complexity of societal situations. Therefore the new sciences [6, 7], in particular networks and complexity, provide excellent new avenues for analysis and prospective insights. As a matter of fact, we may treat networks as patterns or structures while complexity is an implicit property of such structures.

Focusing on new sciences looks like a very promising endeavour, in particular for WAAS. Although the field of these new ‘knowledge producers’ is extremely broad, they provide new understandings, generate specific relationships between actors in many branches of the sciences, and contribute beyond present assumptions.

The new sciences are to be understood as complementary to the ‘classical’ sciences; they ‘uncover’ new relationships, new laws (of mathematical character), and new characteristics among the manifold parameters. Generally, the new sciences enable us to take non-linear relationships within systems into account, which was almost impossible before.

There are several fundamental problems where the application of the sciences of networks and complexity can provide new insights into hitherto purely scientific domains. One example is in the functioning of metabolisms in micro-organisms. Their application in the domain of climate change and the eco-biosphere is also expected to bring a better understanding at the regional and planetary scale. In the fields of sociology and economics, these problems include new methods that enhance diagnostics.

The governance of complex industrialised societies requires a better understanding of their underlying trends and institutional political decision processes. The methods applied so far do not appear to be able to provide appropriate guidelines. New insights into the organisation of very large institutions, ministries, businesses, and international governance bodies, as well as perhaps into the governance of the financial world, require approaches that the sciences of networks and complexity can offer.

For a long time, scientists have expressed the need for cross-domain analysis to overcome the exclusive approach of specialised understanding and arrive at an overarching understanding, denominated as a holistic methodology. Western science and culture from the Renaissance times on have made tremendous progress based on reductionist analytical methods. However, these assumptions are frequently insufficient for a deeper understanding of reality. The well-known phrase, “The whole is more than the sum of the parts” (attributed to Aristotle), is not only correct but now much more practicable than a reductionist approach. With the emergence of Systems Theory, Complexity Science, and related methods, a more holistic understanding is closer to being in the reach of scientific endeavours.

1. The Science of Networks

Several models of networks [8] have been described over time: the *Random Network* is known as the Erdös-Rényi Model [9]; the *Scale-Free Model* is known as the BA Model and called after Barabasi and Albert [10, 11]; and the *Small World Model* is known as the Watts-Strogatz algorithm [12].

It must be stressed that mathematical tools have contributed substantially to the analysis, descriptions, characteristics, and properties of the networks, thus contributing to the understanding of the reality not recognised yet.

1.1 A Model: Scale-free and Power law [13, 14]

Over the past few years, investigators from a variety of fields have discovered that many networks – from the world wide web to a cell’s metabolic system to actors in Hollywood, etc. – are dominated by a relatively small number of nodes that are connected to many other ones.

Networks containing such important nodes, or hubs, tend to be what is called ‘scale-free’, in the sense that a few hubs have a very high number of links and many nodes just a small number of links. The surprising discovery was that these networks do not behave in the expected random behaviour – a generally accepted description of phenomena in physics that results frequently in the well-known ‘bell’ curve coming from a usual statistical distribution – but are characterised by log-log relationships which are called ‘power laws’.

What is important is that the scale-free networks behave in certain predictable ways: for example, they are remarkably resistant to accidental failures but extremely vulnerable to coordinated attacks.

As an example, counting how many web pages had exactly k links showed that the distribution followed a so-called power law: the probability that any node was connected to k other nodes being proportional to $1/k^n$. The value of n for incoming links is approximately two. Power laws are quite different from the bell-shaped distributions that characterise random networks. Specifically, a power law does not have a peak, as a bell curve does (Poisson distribution), but is instead described by a continuously decreasing function. When plotted on a log-log scale, a power law is a straight line. In contrast to the ‘democratic’ distribution of links seen in random networks, power laws describe systems in which a few hubs dominate.

1.2 Some Important Properties of networks

1.2.1 Resilience /Robustness [11]

As humanity becomes increasingly dependent on electricity grids and communications webs, a much-voiced concern arises: Exactly how reliable are these types of networks? The good news is that complex systems can be amazingly resilient against accidental failures. In fact, although hundreds of routers routinely malfunction on the internet at any moment, the network rarely suffers major disruptions. A similar degree of robustness characterises living systems: people rarely notice the consequences of thousands of errors in their cells, ranging from mutations to misfolded proteins.

What is the origin of this robustness? Intuition tells us that the breakdown of a substantial number of nodes will result in a network’s inevitable fragmentation. This is certainly true for random networks: if a critical fraction of nodes is removed, these systems break into tiny, non-communicating islands.

Yet simulations of scale-free networks tell a different story: as many as 80 percent of randomly selected internet routers can fail and the remaining ones will still form a compact cluster in which there will still be a path between any two nodes. It is equally difficult to disrupt a cell's protein-interaction network: measurements indicate that even after a high level of random mutations is introduced, the unaffected proteins will continue to work together.

In general, scale-free networks display amazing robustness against accidental failures, a property that is rooted in their inhomogeneous topology. The random removal of nodes will take out mainly the small ones because they are much more plentiful than hubs. And the elimination of small nodes will not disrupt the network topology significantly, because they contain few links compared with the hubs, which connect to nearly everything. But reliance on hubs has a serious drawback: vulnerability to attacks.

In a series of simulations, it was found that the removal of just a few key hubs from the internet splintered the system into tiny groups of hopelessly isolated routers. Similarly, knockout experiments in yeast have shown that the removal of the more highly connected proteins has a significantly greater chance of killing the organism than does the deletion of other nodes. These hubs are crucial, if mutations make them dysfunctional, the cell will most likely die.

1.2.2 Strengths and Weaknesses

A reliance on hubs can be advantageous or not, depending on the system.

First, one has to note that certainly, resistance to random breakdown is good news for both the Internet and the cell. Besides, the cell's reliance on hubs provides pharmaceutical researchers with new strategies for selecting drug targets, potentially leading to cures that would kill only harmful cells or bacteria by selectively targeting their hubs, while leaving healthy tissue unaffected.

Second, the ability of a small group of well-informed hackers to crash the entire communications infrastructure by targeting its hubs is a major reason for concern.

Some Examples of Applications

Over the past several years, researchers have uncovered scale-free structures in a stunning range of systems which include:

- the *world wide web*;

- some *social networks* (A network of sexual relationships among people (from research in Sweden) followed a power law: although most individuals had only a few sexual partners during their lifetime, a few (the hubs) had hundreds.);
- the network of people connected by *e-mail*;
- the network of *scientific papers* (Connected by citations, collaborations among scientists in several disciplines, including physicians and computer scientists, follow a power law.);
- *business networks* (A study on the formation of alliance networks in the U.S. biotechnology industry discovered definite hubs.);
- the network of *actors in Hollywood* (Popularised by the game Six Degrees of Kevin Bacon, in which players try to connect actors via the movies in which they have appeared together. A quantitative analysis of that network showed that it, too, is dominated by hubs.);
- the *biological realm* (In the cellular metabolic networks of 43 different organisms from all three domains of life, including *Archaeoglobus fulgidus* (an archaebacterium), *Escherichia coli* (a eubacterium), and *Caenorhabditis elegans* (a eukaryote), it was found that most molecules participate in just one or two reactions, but a few (the hubs), such as water and adenosine triphosphate, play a role in most of them.);
- the *protein-interaction* network of cells (In such a network, two proteins are ‘connected’ if they are known to interact with each other. Investigating *Baker’s yeast*, one of the simplest eukaryotic (nucleus-containing) cells, with thousands of proteins, was found to have a scale-free topology. Although most proteins interact with only one or two others, a few can attach themselves physically to a huge number; a similar result was found in the *protein-interaction* network of an organism that is very different from yeast, a *simple bacterium* called *Helicobacter pylori*.).

Indeed, the more scientists studied networks, the more scale-free structures were discovered. These findings raised an important question: How can systems as fundamentally different as the cell and the Internet have the same architecture and obey the same laws? Not only are these various networks scale-free, but they also share an intriguing property: for reasons not yet known, the value of n in the k^n term of the power law tends to fall between 2 and 3.

A compelling question arises: How many hubs are essential? Recent research suggests that generally speaking, the simultaneous elimination of as few as 5 to 15 percent of all hubs can crash a system.

2. The Science of Complexity

2.1 General remarks

The focus of this section lies on the innovative character of this new science, be it in the mathematical domain, the biological domain, or in terms of societal behaviour, in particular in sociology but also economics. Will industrial societies evolve to a new pattern of evolution/development under the influence of these new network facilities created by entirely new technologies? The relationship between individuals, or inter-subjectivity, will depend on the availability and accessibility of network and complexity methodologies. Therefore uncovering new types of relationships enables more sustainable prospective scenarios of how our industrial societies will or could look like by the mid-21st century.

Important issues to be examined are democratic processes through the existence or the ‘spontaneous’ emergence of networks. This new phenomenon becomes an important parameter in electoral campaigns, in major political processes such as the overthrow of leaders, and local and community issues. This very interesting domain is opened for debate and reflection.

The state of knowledge about networking and complexity will play an increasing role in understanding the organisation and functions of societies. Some recent events and tendencies, in a large variety of domains, indicate the richness of the applicability of these sciences: the analysis and search for remediation of the worldwide financial crises; underlying political channels and possible solutions regarding the events of the Arab Spring; the nature and size of social developments in nations with emerging economies; health research and disease dissemination; the impact of diminishing bio-diversity on human society and at planetary scale; etc.

The manifold issues that have not yet found appropriate and durable (sustainable) answers, most likely will find substantial progress with the application of these new sciences. The understanding of such phenomena requires that other types of approaches – more holistic than reductionist – are necessary for improved diagnoses that will result in a better understanding and increased acceptance of proposed solutions.

In the case of world problems, the search for appropriate solutions by the international organisations within the present political frame, shows quite clearly that progress can only be made by other approaches than the one used until now, based on scientific analysis and understanding, and in which these new sciences will play a substantial role.

2.2 The Science of Complexity: Definitions, Properties, and Tools

2.2.1 Definitions

Defining complexity remains a not easy task. Some definitions below are taken from publications and depend strongly on the viewpoint of the authors.

From Melanie Mitchell [6]:

> "Complexity is a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution."

From Roger Lewin [7]:

> "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 of organic and holistic systems that are difficult to comprehend by traditional scientific analysis."

From the OECD Global Science Forum: "Applications of Complexity Science for Public Policy: New Tools for Finding Unanticipated Consequences and Unrealized Opportunities" [13]:

> "Government officials and other decision-makers increasingly encounter a daunting class of problems that involve systems composed of very large numbers of diverse interacting parts. These systems are prone to surprising, large-scale, seemingly uncontrollable, behaviours. These traits are the hallmarks of what scientists call complex systems.
>
> An exciting, interdisciplinary field called complexity science has emerged and evolved over the past several decades, devoted to understanding, predicting, and influencing the behaviours of complex systems.
>
> The field deals with issues that science has previously had difficulty addressing (and that are particularly common in human systems) such as non-linearities and discontinuities; aggregate macroscopic patterns rather than causal microscopic events; probabilistic rather than deterministic outcomes and predictions; change rather than stasis."

2.2.2 Some Properties

The promise of complexity science for policy applications is, at its core, the hope that science can help anticipate and understand the key patterns in complex systems that involve or concern humans, thus enabling wiser decisions about policy interventions.

Some important characteristics of complex systems are:

- *adaptability*: independent constituents interact changing their behaviours in reaction to those of others, and adapting to a changing environment;
- *emergence*: a novel pattern that arises at system level not predicted by fundamental proprieties of the system's constituents;
- *self-organisation*: a system that operates through many mutually adapting constituents in which no entity designs it or directly controls it;
- *attractors*: some complex systems spontaneously and consistently revert to recognisable dynamic states known as attractors. While they might, theoretically, be capable of exhibiting a huge variety of states, in fact, they mostly exhibit the constrained attractor states;
- *self-organised criticality*: a complex system may possess a self-organising attractor state that has an inherent potential for abrupt transitions of a wide range of intensities. In a system that is in a self-organised critical state, the magnitude of the next transition is unpredictable, but the long-term probability distribution of event magnitudes is a very regular known distribution (a 'power law');
- *chaos*: chaotic behaviour is characterised by extreme sensitivity to initial conditions;
- *non-linearity*: non-linear relationships require sophisticated algorithms, sometimes probabilistic. Small changes might have large effects while large changes could have little or no effects;
- *phase transitions*: system behaviour changes suddenly and dramatically (and, often, irreversibly) because a 'tipping point', or phase transition point, is reached. Phase transitions are common in nature: the boiling and freezing of liquids, the onset of superconductivity in some materials when their temperature decreases beyond a fixed value, etc;
- *power laws*: probabilistic distribution characterised by a slowly decreasing function (log-log), different from the 'familiar' bell-shaped one.

2.2.3 Tools and Techniques for Complexity Science

Some of the most important complexity tools being used in public policy domains at this time are:

- *agent-based* or Multi-agent Models: in computerised, agent-based simulations, a synthetic virtual 'world' is populated by artificial agents who could be individuals, families, organisations, etc. The agents interact adaptively with each other and also change with the overall conditions in the environment;
- *network analysis*: a common feature of many complex systems is that they are best represented by networks, which have defined structural features and follow specific dynamic laws. Scientists seek to identify configurations that are especially stable (or particularly fragile). Some network patterns have been identified as predictors of catastrophic failures in real-life networks, such as electricity distribution networks or communications infrastructures.

Additional complexity-related techniques deserve special mention, although their use is not unique to complexity science: Data Mining, Scenario Modelling, Sensitivity Analysis, Dynamical Systems Modelling.

2.3 Possible Applications in the Public Policy Domain

Several examples of application domains have been or are being explored; e.g. epidemiology and contagion, traffic, identification of terrorist associations, etc. Of more general interest is climate change, in particular, the social and human aspects – the connection between economy, finance, energy, industry, agriculture, and the natural world. These new degrees of sophistication can only be achieved using complexity science.

Complexity science techniques can be useful in identifying dangerous tipping points in the human-earth system, which can occur independently of purely geophysical transitions. Perhaps the most likely disruption of this type involves the management of water resources. Drought and water stresses occur regularly across large sections of Europe and the developing world. There are indications that a tipping point may be near, leading to massive long-term water shortages.

2.4 A Recent Topic: Economic complexity [15]

The recently published “Atlas of Economic Complexity” and the Economic Complexity Indicator (ECI) defined in that publication have largely inspired what follows.

Gross Domestic Product (GDP) and the growth thereof are the two most used indicators to measure the level of economic activity and its evolution in terms of economic growth. GDP per capita is used to express the average richness of a population of a country. However, GDP remains lacking when it comes to evaluating the well-being of society.

Many attempts have been undertaken to improve or find better indices to express real progress in well-being. Within the framework of the Science of Complexity an interesting approach has been proposed, rather recently, with the creation of the Economic Complexity Indicator (ECI), which focuses on the structure of the economy of a country and enables the diagnosis of its further development or progress, essentially based on the amount of knowledge available in society for producing goods and services.

In a way, the ECI shows substantial progress in the evaluation of the economy of a country compared to the GDP. The many attempts to elaborate a ‘new’ economic system cannot overlook this innovative approach in using new sciences such as complexity.

2.4.1 What is Economic Complexity [16]

The complexity of an economy is related to the multiplicity of useful knowledge embedded in it. For a complex society to exist, and to sustain itself, people who know about design, marketing, finance, technology, human resource management, operations, and trade laws must be able to interact and combine their knowledge to make products. These same products cannot be made in societies that are missing parts of this capability set. Economic complexity, therefore, is expressed in the composition of a country’s productive output and reflects the structures that emerge to hold and to combine the knowledge.

Knowledge can only be accumulated, transferred, and preserved if it is embedded in networks of individuals and organisations that put this knowledge to productive use. The knowledge that is not used – at least in this economic context – is not transferred and will disappear once the individuals and organisations that have it retire or die.

Complex economies are those that can weave vast quantities of relevant knowledge together, across large networks of people, to generate a diverse mix of knowledge-intensive products. Simpler economies, in contrast, have a narrow base of productive knowledge and produce fewer and simpler products, which require smaller webs of interaction. Because individuals are limited in what they know, the only way societies can expand their knowledge base is by facilitating the interaction of individuals in increasingly complex webs of organisations and markets. Increased economic complexity is necessary for a society to be able to hold and use a larger amount of productive knowledge, and we can measure it from the mix of products that countries can make.

2.4.2 The Economic Complexity Index (ECI) and the Product Complexity Index (PCI)

First, the amount of embedded knowledge that a country has is expressed in its productive *diversity* or the number of distinct products that it makes. Second, products that demand large volumes of knowledge are feasible only in the few places where all the requisite knowledge is available. We define *ubiquity* as the number of countries that make a product. Using this terminology, we can observe that complex products – those that are based on much knowledge – are less ubiquitous. The ubiquity of a product, therefore, reveals information about the volume of knowledge that is required for its production. Hence, the amount of knowledge that a country has is expressed in the diversity and ubiquity of the products that it makes.

The Economic Complexity Index (ECI) refers to countries. The corresponding measure for products gives us the Product Complexity Index (PCI). The mathematical approach exploits the combination of these indices as well as diversity and ubiquity to create measures that approximate the amount of productive knowledge held in each country.

In short, economic complexity matters because it helps explain differences in the level of income of countries. More importantly, it can help predict future economic growth. Economic complexity might not be simple to accomplish, but the countries that do achieve it, tend to reap important rewards.

3. Complexity Science: New Ways of Thinking for Policymakers

The suggested new ways of thinking to focus the attention of policymakers on dynamic connections and evolution, not just on designing and building fixed institutions, laws, regulations, and other traditional policy instruments, are [13]:

- *predictability*: complex systems science focuses on identifying and analysing trends and probabilities, rather than seeking to predict specific events. It will be challenging, though necessary, for policymakers and scientists alike to move beyond strict determinism if they wish to effectively engage in decision-making under conditions of uncertainty and complexity.
- *control*: control is generally made possible by identifying cause-and-effect chains and then manipulating the causes. But cause and effect in complex systems are distributed, intermingled, and not directly controllable. Complexity science offers many insights into finding and exploiting desirable attractors; identifying and avoiding dangerous tipping points; and recognising when a system is in a critical self-organising state.
- *explanation*: when analyses were done using complexity science methods, insights about the underlying mechanisms that lead to complex behaviour were revealed. Although deterministic quantitative prediction is not generally achieved, the elucidation of the reasons for complex behaviour is often more important for comprehending otherwise puzzling real-world events.
- *changing the mindset*: understanding the basic ideas of the complexity of the world together with its unpredictability. One should not forget that W. Cameron has warned: “Not everything that counts can be counted, and not everything that can be counted, counts.”

References

[1] J. Curry, The complexity turn. *Theory, Culture & Society*, 2005, 22, 5, 1-14.

[2] B. Castellani and F. Hafferty, *Sociology and Complexity Science. A New Field of Inquiry*. Springer, 2009.

[3] I. Wallerstein, *World-Systems Analysis. An Introduction.* Duke University Press, 2004.

[4] Merriam-Webster Online, http://www.merriam-webster.com/dictionary/cybernetics (Accessed Dec. 15, 2012)

[5] D.H. Meadows et al., *The Limits to Growth.* Universe Books, 1972.

[6] M. Mitchell, *Complexity. A Guided Tour.* Oxford University Press, 2009.

[7] R. Lewin, *Complexity. Life at the Edge of Chaos*. Phoenix, 1993.

[8] E.J. Newman, *The structure and function of complex network*s. 2003: arXiv:cond-mat/0303516v1

[9] S. Boccaletti et al., *Complex Networks: Structure and dynamics*. Elsevier, Physical Reports, 2006, 424, 175-308.

[10] A.-L. Barabási, *Linked. The New Science of Networks*. Perseus Publishing, 2002.

[11] A.-L. Barabási and E. Bonabeau, *Scale-Free Networks.* Scientific American, May 2003.

[12] D.J. Watts, *Six Degrees. The Science of a Connected Age.* W.W. Norton & Co., 2003.

[13] OECD, *Report on Applications of Complexity Science for Public Policy: New Tools for Finding Unanticipated Consequences and Unrealized Opportunitie*s. September 2009.

[14] G. Weisbuch and S. Solomon, *Tackling Complexity Science*. EC, 2007.

[15] R. Hausmann, C.A. Hidalgo et al., *The Atlas of Economic Complexity. Mapping Paths to Prosperity*. MIT, 2011: http://atlas.media.mit.edu

[16] G. Caldarelli, M. Cristelli, A. Gabrielli, L. Pietronero, A. Scala, and A. Tacchella, Ranking and clustering countries and their products; a network analysi*s*, *PLoS ONE*, 01/2012, 7(10): e47278.