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EDITORIAL

Complex systems in the spotlight: next steps after the 2021 Nobel Prize in Physics

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Abstract

The 2021 Nobel Prize in Physics recognized the fundamental role of complex systems in the natural sciences. In order to celebrate this milestone, this editorial presents the point of view of the editorial board of JPhys Complexity on the achievements, challenges, and future prospects of the field. To distinguish the voice and the opinion of each editor, this editorial consists of a series of editor perspectives and reflections on few selected themes. A comprehensive and multi-faceted view of the field of complexity science emerges. We hope and trust that this open discussion will be of inspiration for future research on complex systems.

Contents

Celebrating complex systems in honor of the 2021 Nobel Prize in Physics

The 2021 Nobel Prize in Physics was awarded 'for groundbreaking contributions to our understanding of complex physical systems' with one half jointly to Syukuro Manabe and Klaus Hasselmann and the other half to Giorgio Parisi. As editors of *JPhys Complexity* we would like to congratulate the Nobel Laureates for their extraordinary achievements that have deeply transformed the way we look at the Earth system and at complex systems in general. To paraphrase the press release for the 2021 Prize [1], the Laureates have laid the foundation of our knowledge of the Earth's climate and how humanity influences it, as well as revolutionizing the theory of disordered materials and random processes.

In honor of the 2021 Nobel Prize in Physics this editorial of JPhys Complexity aims at reflecting on the progress that complex system research has achieved so far, it aims to identify key scientific, environmental and societal challenges of the field and to outline the prospects for the next twenty years of research on complexity. To preserve the originality of the personal opinions we have structured this editorial as a series of contributions in which each editor reflects on the following themes taking into consideration the specific questions:

- **Defining complex systems.** The definition of complex systems has been highly debated in the past: how would you define complex systems?
- **Biggest challenges in the next twenty years.** What are the biggest challenges of complexity science in the next twenty years?
- **Implications of the 2021 Nobel Prize.** What does the 2021 Nobel Prize imply for research in complex systems?
- **Robustness and fragility of complex systems.** Complex systems are typically described as robust. Yet from climate change to understanding the origin of diseases some of the most pressing challenges in complexity science regard the response to perturbations that significantly affectthe functioning of complex systems. The 2021 Nobel Prize was awarded for research identifying the role of perturbations and fluctuations in complex systems. Can you comment on the interplay between robustness and fragility of complex systems? Can you identify key scientific problems that highlight this interplay?
- **Prediction in/with complexity.** Complexity remains one of the scientific disciplines in which prediction is more challenging. Why is so? Can we learn from success stories?
- **Advantages and challenges of interdisciplinary research.** Complexity science is an interdisciplinary field. What are the advantages and what are the challenges of interdisciplinary research in complex systems?
- **Final comments.** Is there anything else you would like to state in celebration of the Nobel Prize 2021?

Each editor has provided their contribution independently without reading the contributions by the other editors bringing a different perspective on complex systems. Consequently the editorial as a whole presents a comprehensive view of the key challenges of the field. Even for the questions in which there is a wide spread consensus on the answer, this editorial achieves the important outcome of testifying the extent of this consensus, at least among the editors of JPhys Complexity. For instance, from this editorial a significant consensus emerges on the definition of complex systems, as a systems composed of many elements and displaying emergent phenomena. This should not by any means be taken for granted, as the definition of a complex systems has been historically very widely debated in the literature (for a critical discussion see Janos Kertesz' contribution). Other notable subjects in which there is wide spread consensus include the fundamental role of networks in encoding the underlying structure of complex systems. From the dynamical point of view this editorial also highlights the ubiquitous presence of stochasticity, randomness and nonlinearities. Taken together, these facets imply that any prediction of the dynamical state of a complex system is typically bound to be of a probabilistic nature.

We would like to think about this editorial as a symphony consisting of harmonic combinations of different movements in which the 'whole is more than the sum of its parts'. In particular, this editorial contains leitmotifs of widely accepted concepts and ideas that provide a very solid common ground. At the same time, many observations remain individual and highly personal and original, reflecting the different foci of the research of the *JPhys Complexity* editors.

This editorial can be read all in one go or alternatively accessed and read slowly by browsing the contributions of the individual editors in the table of content according to the curiosity of the reader in knowing the response of each editor to the selected list of questions.

It is our hope that the readers of this editorial will appreciate the different insights presented and discussed in the contributions here enclosed and that this editorial will provide a general perspective on complex system research which will be a source of inspiration for future works in the field.

The editorial is structured as follows: the first opening perspective by Editor-in-Chief Ginestra Bianconi, is followed by the perspectives of the editors listed in alphabetical order.

1. Perspective of Ginestra Bianconi

Ginestra Bianconi[1,2]

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- **Defining complex systems**

Although the definition of complex systems has been historically widely debated, I believe that currently there is a wide agreement on one specific definition: a complex system is formed by many interacting elements that give rise to emergent phenomena. However, this definition leaves some terms unspecified. For instance: how many elements are enough to display complex emergent phenomena? Interestingly this number can be large like the number of neurons and synapses in the human brain but can be also relatively small as we known that the brain of the worm *Caenorhabditis elegans* is formed only by few hundreds neurons while the worm can display a very non trivial behavior. The minimal cell as well is formed only by few hundred genes and is already alive. From these examples it emerges that really complexity and emergent phenomena require a number of elements that can be very far from the large numbers usually considered in physics (the number of molecules in a mole of gas are given by the Avogadro number i.e. about 6×10^{23}).

It seems a very well accepted idea that complexity arises from the competition between randomness and order and that the underlying topology of a complex system is inherently related to a certain amount of randomness in the network of interactions between its elements (network approach [2]) or in the sign of their interactions (spin-glass approach [3]).

Despite the impressive progress of complexity science that has been made in the last 50 years, I think that we are still far from fully understanding complexity as we have not yet identified the necessary conditions for a system to display complex emergent phenomena. For instance, we are quite far from fully understanding brain function. As a result of this, the field might look fragmented when compared with other more traditional scientific fields for instance in physics. However, I like to see this aspect of the research of complex systems as a benefit and a richness of the field. Indeed I believe that to tackle complexity we really need to explore different aspects of complex systems and we need to adopt an open-minded point of view that is able to describe and predict complex systems data avoiding pre-defined top-down dogmas.

- **Biggest challenges in the next twenty years**

Complexity science faces some of the most pressing challenges in terms of their impact to society and their urgency for humankind. The Nobel Prize recognition to Syukuro Manabe, Klaus Hasselmann and Giorgio Parisi for their research in complex systems was long due and it is my hope that this Nobel Prize will contribute to a wider societal recognition of the need to address the pressing problem of climate change.

Clearly the research on climate change whose pioneers have been recognised by the Nobel Prize 2021 is a top priority and its relevance and urgency cannot be overstated [4, 5]. The field is rapidly expanding and will require combining an interdisciplinary approach to tackle the challenges posed by raising temperatures to climate, to the environment and to the ecosystems in the near future. Climate change is also important from the perspective of social sciences, as understanding how the human society responds to climate change and suggesting ways to improve global cooperation is extremely important for the future of the planet.

Complexity science is also key to understand and predict the evolution of large pandemics and to inform policy makers and the general public about the risks of epidemic spreading. Indeed the network science community was already aware well before Covid of the danger of global pandemics taking advantage of the scale-free global transportation systems [6]. Unfortunately though the pandemic took most of the countries by surprise as the contingency plans where not really ready for an epidemic of the scale of the Covid-19. In order to monitor the evolution of this pandemic and any future one scientists are likely to combine the large amount on data on social mobility, with prediction the models that are key to monitor the pandemics and to inform policy makers, despite the many uncertainties about the biological evolution of the viruses.

In the next twenty years progress at the interface between complexity and biology will be key to make much needed advances on precision medicine. This big complexity challenge will require a truly interdisciplinary approach combining network science, machine learning and AI with molecular biology and neuroscience. Indeed while biology in the past decades has been pursuing extensively the single molecule approach or relying heavily on the central dogma of molecular biology, it is now well recognized that most of the diseases are complex and for understanding these diseases it is important to embrace the complexity and the heterogeneity of the interacting networks of the cell. In neuroscience brain research is flourishing yet the complexity of the system which is inherently multiscale and enriched at the molecular level by a formidable richness of the combinatorics of the interactions which still constitute a challenge for a global understanding of brain function.

Finally in the next twenty years complexity will be key for putting the foundation for the quantum Internet which will require combining the progress on quantum information with our understanding of classical complex communication systems such as the current Internet.

- **Implications of the 2021 Nobel Prize**

The Nobel Prize 2021 brings awareness of the importance of climate change and it is a statement regarding the authority of research in complex systems. Historically stochastic dynamics has been very much considered borderline in physics, and even quantum mechanics that has a probabilistic nature is dictated by a deterministic equation of motion (the Schrödinger equation is deterministic). However, stochasticity is fundamental for research on complex systems ranging from climatology to spin glass and to complex networks, and, expanding the range of subjects beyond physics, it is fundamental in biology, social science and even engineering. The Nobel Prize 2021 recognizes that complex systems whose dynamics is driven by randomness and stochasticity is a main-stream subject that deserve the highest scientific prize [3–5, 7, 8]. This is of invaluable importance for the full complex system community, and will boost the research on the field and hopefully also its funding. The Nobel Prize 2021 is a big step for society and a further prestigious recognition to the scientific research in climate change that has been very much challenged by misinformation campaigns.

- **Robustness and fragility of complex systems**

Complex system research embracing the stochastic and random nature of complex systems has now been fully recognized by the Nobel Prize in 2021. However progress is necessary for understanding further the relation between robustness and fragility of complex systems. For instance, a pressing question is: how far we are for tipping points in climate?

Another important application of network robustness is in brain research as brain is a undoubtedly a robust complex system however it is very important to understand how its function is affected by diseases. In order to tackle this question I believe that we need to embrace the stochastic nature of brain activity and gain further understanding of the interplay between brain function and the brain network topology.

Thanks to the fundamental achievements of network science, we already know that the robustness of networks to random damage depends strongly on the statistical properties of the network. Indeed, the scale-free degree distribution of networks changes dramatically the phase diagram of percolation displaying a critical behavior that is dramatically different from percolation on regular lattices or on random graphs [9–12]. These results have been pivotal to understand the interplay between the underlying network structure of complex systems and their dynamics. In my opinion, further progress in understanding the interplay between network and higher-network topology and dynamics will likely arise from the use of tools coming from applied topology and stochastic geometry. In part this is already happening [13, 14] and I think that adopting topological and geometrical arguments to understand dynamics on complex networks and higher-order networks can be a turning point to uncover some of the outstanding mysteries of brain research and in general in complex systems.

- **Prediction in/with complexity**

Prediction of complex systems is challenging and of course limited by the ubiquitous non-linearities of their dynamics. However important progress in predicting complex systems has been achieved in the last twenty years (for instance think of the unprecedented progress in predicting epidemic spreading). The improvement in prediction power of complex systems is mostly due to the large amount of data that is available to modellers and the important progress that complexity science combined with data science and artificial intelligence (AI) can achieve. Interestingly in complexity science it occurs quite often that improved prediction power comes at the cost of using black-box tools which play a major role in AI and this brings intrinsic risks when using these tools. I strongly believe that enhancing our prediction power of complex systems eventually combining network science, data science and AI algorithms, is really key for a variety of applications including most significantly providing possible scenarios in climate change. However, the power of simple models to understand complex systems is of outermost importance for interpretability of the results: simple models might not capture all the details of complex systems but are our hope to understand and taming complexity and I believe they are crucial also to devise better AI algorithms. Spin-glass theory teaches us that a model that is actually quite simple (just adding a random mixture of positive and negative interactions to the Ising model on a fully connected network) can be already very complex [3]. Similarly, just considering scale-free networks with a power-law degree distribution can dramatically change the dynamics defined on a network affecting the phase diagram of critical phenomena [12]. The benefit of these simple models is enormous as it allows us to identify the very pivotal effect of key properties of complex systems such as the heterogeneity in the sign of the interactions or the heterogeneity in the number of interactions of each element of the complex system.

- **Advantages and challenges of interdisciplinary research**

The advantage of interdisciplinary research is that the field is inclusive and enriched by the different perspectives provided by scientists in different disciplines. This allows to tackle questions related to the universal common properties of complex system from a bottom-up perspective that is fundamental and complementary to the top-down approach that has been dominating complexity in the previous century. Moreover, interdisciplinarity allows to avoid self-referential traps as the field is rapidly evolving due to the inclusion of new research problems, new mathematical tools, and new experimental results coming from different disciplines.

One important challenge of interdisciplinary research is formulating a common language that is accepted across different disciplines. Network science and machine learning have faced this challenge and are to large extent accepted frameworks in different disciplines. However, when writing an interdisciplinary paper, developing a common language implies also sharing common priorities and alignment of the focus of scientific attention, and in this regard many differences remain. Moreover, the research style of different disciplines varies (such as timing for writing an article, convention on author list order, journal publication versus conference publications, etc). Therefore, an interdisciplinary collaboration might require some adaptation skills of the involved scientists to each other way of working.

- **Final comments**

My sincere congratulations to the Nobel Prize 2021 winners for their fantastic achievements and for expanding the realm of fundamental research to complex systems! I would like to also extend the congratulations to the entire community working on complex systems and tackling the many challenges of the field from different perspectives. Finally, a special thanks goes to the editors of JPhys Complexity that have contributed to this editorial. I hope that the collective vision of complexity emerging from this editorial will be a reference point for the future development of the field.

2. Perspective of Alex Arenas

Alex Arenas

Universitat Rovira i Virgili, Spain

- **Defining complex systems**

As I understand, a complex system is a distributed set of entities with many interconnections (usually networked), where each entity self-operates locally with its neighboring entities, and exhibiting globally emergent behavior. This simple yet abstract definition of a complex system is compatible with the myriad of systems that have been called 'complex' in different disciplines.

- **Biggest challenges in the next twenty years**

The major challenge of complexity science is to develop a close-form theory ruling the emergent behavior of complex systems. I think that such theoretical framework is attainable thought the confluence of tensorial algebra, statistical and non-linear physics, and spectral theory.

- **Implications of the 2021 Nobel Prize**

The Nobel Prize 2021 represents the highest achievement for the complex systems community to be accepted as fundamental physics of the next centuries.

- **Robustness and fragility of complex systems**

Robustness and fragility in complex systems, in my opinion, must be understood in terms of propagation. The more robust is the system to perturbations, the more difficult is to propagate in this system any other property from local to global, and the contrary for the fragility. The more fragile is the system to perturbations, the easier is to propagate in this system any other property from local to global. Difficult and easy here, refer to the timescale associated to propagation processes. Understanding robustness and fragility from the point of view of perturbation theory is a key aspect of the development of complex systems analysis.

- **Prediction in/with complexity**

Generally speaking, I think that the challenging in prediction comes from the non-linearity associated to the interactions in the absence of symmetries. Nevertheless, predictions can be achieved using approximations, has it has been the case in the rest of fields within the physics realm. Predictions about the evolution of epidemics are clear examples of the power of our field in the real world.

- **Advantages and challenges of interdisciplinary research**

As an interdisciplinary field, the advantages are in the huge quantity of scientific scenarios that can be approached with a complex systems perspective. The challenges, as in any other interdisciplinary field, are that of constructing a common language, and a shared approach.

- **Final comments**

I congratulate the complex system community for so many years of effort to have relevant presence in the physics community.

3. Perspective of Jacob Biamonte

Jacob Biamonte

Yanqi Lake Beijing Institute of Mathematical Sciences and Applications, People's Republic of China

- **Defining complex systems**

In my experience, many modern scientists adopt an implicit reductionism-centric view. I have seen this in two ways. The first is when a theorist thinks that any description can be reduced to the fundamental laws of nature. The second is when a theorist dreams of a world described through an accurate description of increasingly smaller building blocks. Let us consider the first. For example, both Kepler's laws of planetary motion and Galileo's theories of motion for terrestrial objects are reducible to Newtonian mechanics. All the explanatory power of the former are contained within the latter: this pleases the reductionist. The second case might even describe the modern approach to engineering. Imagine a new Corvette, a beautiful car. A separate team of engineers is responsible for the exact workings of each component forming this machine. To understand the workings of the car, we just have to break things down into smaller parts which we can understand. Again, this appears to add credence to the reductionist. The problem with both approaches—however beautiful reductionism may be—it can fail. Maybe you can even argue that a given theory should always have a relationship back to something more fundamental. Yet the utility of this fundamental theory quickly becomes questionable—often resulting in an impractical theory. The problem arises when faced with making a prediction with 'the more fundamental description'. What if doing so would require a calculation that would take the age of the Universe (or longer) to complete? For example, when the composition of interacting systems results in a system that could—in theory—occupy a number of physical states greater than the number of electrons in the visable Universe. One does not have to look far to find such systems, the computer in front of you is one of them, modern quantum processors being built at Google and IBM represent others. The collective behavior of such systems, it becomes extremely difficult to predict and many predictions being made are based on dramatic departures from the *ab initio* description of their building blocks. I suspect the debate regarding the definition stems from the fact that there are so many distinct complex systems. One interesting discovery made over several decades by leading network scientists is that so many complex systems share relevant properties. These properties can be reflected in the graph used to model a complex systems interactions. Another interesting approach to complexity comes from computer science. Computer scientists separate problems into classes and try to determine lower bounds on the resources (computational steps) required to solve any problem in a class. Many of complex systems that are being studied can easily model universal computation.

- **Biggest challenges in the next twenty years**

You might call me biased, but a quantum theory of complex networks is lacking still. That is not to say that interesting results have not taken place. For example, the Bianconi–Barabási theory already related network scaling laws to Bose–Einstein condensation [15] in 2001. Many subsequent papers have built on these findings. The theory of quantum information has started to have increasingly wide impacts on physics and even technology. In 2010 Perseguers, Lewenstein, Acín and Cirac found that quantum effects in random networks produce rather unexpected subgraphs of connections to appear [16]. These and other results have attracted interest—see for instance the review I have written with Facin and De Domenico [17]. Whereas a multitude of networks appear in connection to quantum theory, the relationship between properties of networks and quantum effects is not entirely understood.

- **Implications of the 2021 Nobel Prize**

According to Philip Anderson (Nobel Laureate 1977), 'the history of spin glass may be the best example I know of the dictum that a real scientific mystery is worth pursuing to the ends of the Earth for its own sake, independently of any obvious practical importance or intellectual glamour'. I think that the Nobel prize brings much more attention to the wonderful world of spin glasses. One aspect we might not always want to talk about is that a lot of complexity research is done by physicists working in applied mathematics and computing departments around the world. Maybe the 2021 Nobel will widen the role such topics play inside of physics departments?

- **Prediction in/with complexity**

Many results exist which show that complex systems can readily emulate universal computers. Moreover, many authors have argued that phase transition points, are among the most difficult to computationally model. I think that the success stories come from not trying to tackle problems that appear impossible. Indeed, prediction of certain system properties can be more difficult whereas other properties, even in the average cases, we can determine them without much knowledge (or calculation) of the system.

- **Advantages and challenges of interdisciplinary research**

I entered the field to work toward a quantum theory of complex networks. The topic was interesting as quantum effects do not always appear to correlate with evident network properties, whereas many properties of traditional complex systems do. I guess the advantage is to work on interesting new topics. The disadvantage could be that the research does not always clearly fit into a defined subject.

- **Final comments**

Replica symmetry breaking (I believe) is a beautiful and timeless theory. The wonderful everlasting language of spin glasses, so many have approached glasses in such a range of different ways. Yet I think that Giorgio Parisi's work will bring greater awareness to the oldest and most successful theories related to glasses. This is especially important as there's a new generation tackling variants of these problems from a completely different perspective. Some of these researchers have backgrounds more in quantum theory and condensed matter (actually rather distant from the traditional statistical mechanics) and others with backgrounds entirely in computer science and neural networks. It is not the first time that the field of complex systems has crossed into other domains through the language of spin glasses. If history tells us anything, it will not be the last and there's plenty more to learn.

4. Perspective of Lincoln D Carr

Lincoln Carr

Colorado School of Mines, United States of America

- **Defining complex systems**

Thurner, Hanel, and Klimek (THK) have an excellent recent book, *Introduction to the Theory of Complex Systems* [18], in which they posit that complex systems are co-evolving multilayer networks of interacting elements. In their view of complexity, interactions are captured by a three index tensor $M_{ij}^{\alpha}(t)$ and the states of their elements are indicated by the time-dependent functions $\sigma_i(t)$. While I am not sure this captures all aspects of observed physical complexity, it does give rise to a surprising number of common mathematical features we identify throughout nature in many different systems. In contradistinction to the hypotheses of pure empiricism, confirmation bias, or human pattern-identifying tendencies, it is these pervasive mathematical commonalities that after some time spent doing research in the field become irrefutable, and we call 'complex systems'.

- **Biggest challenges in the next twenty years**

Transitioning complexity science from a set of empirically identifiable mathematical commonalities between disparate physical systems to *physical* complexity classes might be a couple of century problem, not just a couple of decade problem. However, considering the enormous recent progress in *computational* complexity classes—as distinct from the physical complexity we are discussing here—and the growing breadth of applicability of physical complexity concepts and mathematical identifiers, I believe we can hope to make significant progress in the next 20 years. I identify physical complexity with (1) nontrivial non-Markovian environments, (2) multiscale hierarchies, (3) persistent dynamical macrostates, (4) non-Gaussian or 'fat-tailed' statistics, (5) fractional geometries, (6) astronomically large and yet high structured probability spaces, (7) the presence of multiple constraints and trade-offs, (8) diversity, (9) selection principles, and of course (10) complex networks. Whether or not the origin of these 10+ axes or aspects of complexity be a single mathematical concept, as THK have suggested, we certainly lack a set of physical postulates from foundational physics that give rise to such a concept or concepts. To me that is the ultimate question in complexity—why is it here?

- **Implications of the 2021 Nobel Prize**

For me the most important outcome of the 2021 Nobel Prize is highlighting how necessary complexity science is to understanding and solving the world's most pressing ecological and environmental problems. How will we address the apocalyptic issues facing us as a species? It is not enough to understand gravity and quantum mechanics, energy and entropy, or even how to engineer a robust circuit. Control theory, geoengineering, and ecology are steps in the right direction. But ultimately addressing global climate change is going to require a systems approach with a deep knowledge of complexity across many fields. The 2021 Nobel Prize is wonderfully interdisciplinary, from climate modelling and the CO_2-heat link, to disordered complex materials. This is the second lesson of the 2021 Nobel Prize: we need interdisciplinarity to move forward. Physics by itself is not enough.

- **Robustness and fragility of complex systems**

The trade-off between robustness and fragility is written of quite beautifully in the review by Carlson and Doyle [19]. In this paper, highly optimized tolerance, a set of concepts drawn from control, communications and computing, is posited as a foundational predictive theory of complexity tying together examples from biology, engineering, etc, e.g. cells and CPUs. Highly optimized tolerance relies heavily on the interplay between robustness and fragility, and is posited to present an alternate and more effective set of explanatory or predictive principles than self-organized criticality, a favorite topic of physicists.

Lately a growing sub-community within the complexity sciences have been working on understanding complexity in entangled quantum systems [20], in particular in the context of noisy intermediate scale quantum (NISQ) computers. The quantum context creates surprising twists on the complexity story, such as the interplay between pre-programmed complexity in the quantum circuit vs emergent complexity in the quantum state [21, 22]. However, one strong common feature with classical complexity is robustness and fragility.

A historical topic in complexity science is cellular automata. Originally thought to provide a potential unifying theory of physics, in fact they are much better at producing complexity. A collection of simple elements with local interactions give rise to a wide range of emergent behavior. For instance, elementary cellular automata are about as simple as one can imagine: one dimension, nearest-neighbor, and built on classical bits. Yet they give rise to randomness, fractals, and even Turing complete computation. Quantum cellular automata generalize the concept from classical bits to quantum bits (qubits) and a local bit-wise update rule to conditional unitary operators; however, the concept is basically the same. It is exactly the trade-off or Goldilocks rule [23] in reversible quantum cellular automata which creates an interplay between robustness and fragility in quantum systems. Entangled quantum states are inherently fragile, and can endure a limited total set of quantum operations before they fall apart, or decohere. This means NISQ calculations are normally limited by the circuit volume: the total circuit depth times the number of qubits, loosely speaking. Goldilocks quantum cellular automata create a new level of robustness. They create complexity for an arbitrary number of qubits, and are limited only by circuit depth [24]. This is not yet error correction, but it is an application of the robustness-fragility trade-off inherent in complex systems to produce rather extraordinary results in NISQ computers.

- **Prediction in/with complexity**

Complexity science is a very young field. I believe its present predictive limits stem primarily from a lack of fundamental principles. Let us consider quantum mechanics as a positive example. A large amount of empirical data in spectroscopy from Newton forward led to the observation of mathematical patterns. Those mathematical patterns in turn created the opportunity for a shift in perspective, namely from classical particles to probability waves as foundational. From the puzzles of spectroscopy to experimental observations supporting the atomic theory of matter, three centuries of scientific investigations led to the dawning realization that a new perspective was needed. The ramifications of the postulates of quantum mechanics are still unfolding in technological applications today in quantum information science and technology. Complexity, like the experiments leading to quantum mechanics, presents many puzzling results that do not seem to fit with our basic notions of statistical physics. What foundational theories predict it? Why is it so commonly observed, across so many fields at so many widely varying scales, from quantum computers to the brain to the planet?

It remains to be seen if complexity theory, like chaos theory with classical physics, will require a shift in perspective of a known theory, perhaps a reformulation of statistical physics and information theory; or whether, like quantum mechanics, complexity will require a truly new paradigm. When we have answered this question, I believe complexity science will become predictive.

- **Advantages and challenges of interdisciplinary research**

I sometimes feel we physicists have a particular view of complex systems. I enjoy learning the perspective from books in other fields, for example Scott Page's *Diversity and Complexity* [25]. Each of us from across many disciplines working in this field tends to identify complexity with our favorite feature, be it complex network structure or natural selection. The question is, how do we find a theory of complexity that really captures these different emphases we each prefer, in such an extraordinarily interdisciplinary environment?

The ultimate challenge in such an interdisciplinary field is really learning the art of listening. I particularly admire the Santa Fe Institute for having created an environment in which biologists, economists, physicists, and many others really sit down, listen, and learn from each other.

- **Final comments**

It is an honor to be in a field inspired by such fantastic early thinkers, and recently recognized with the Nobel Prize in Physics. As an undergraduate student I recall hearing of 'the death of physics', as if the big problems at the time, such as neutrino oscillations, would shortly be solved for good. I think this Nobel Prize shows just how much physics as a perspective continues to expand and amaze. Not only does it amaze, but it really *matters* for the well-being of humanity.

5. Perspective of Byungnam Kahng

Byungnam Kahng

Korea Institute of Energy Technology Naju, Republic of Korea

- **Defining complex systems**

I would say that complex systems are defined by our limitation in predicting their responses to perturbations when starting exclusively from the knowledge of the functioning of their constitutive elements.

- **Biggest challenges in the next twenty years**

The most pressing challenge is to collect Big Data quantifying the response of complex systems to perturbations and to infer the causal relations extracting meaningful and interpretable conclusions.

- **Implications of the 2021 Nobel Prize**

This Nobel Prize clearly implies that for answering fundamental questions about complex systems we need to give up our expectation of any deterministic answer. Instead, we should acknowledge that the correct and the most insightful answers are probabilistic.

- **Robustness and fragility of complex systems**

As I answered to the preceding question, we need to change our way of thinking. For instance, we need to describe the response of complex system to perturbations in a probabilistic way.

- **Prediction in/with complexity**

The internal structure of complex systems is too complicated to respond to a given perturbation in an unique deterministic way. Indeed nonlinearities imply that small variations in the initial condition can lead to very different outcomes. Therefore also prediction needs to take account the uncertainties related to the non-linearities. As a consequence prediction models needs to include confidence levels on the predicted scenarios. Weather forecast can be taken as an example of probabilistic predictions to which we have become rather familiar. For instance, nowadays, the weather forecast tells us, 'tomorrow it will rain with 60% confidence'.

- **Advantages and challenges of interdisciplinary research**

Complexity scientists get used to capture diverse phenomena into simple models. However, non-scientifically trained people often cannot understand the power of this approach. I believe that more effort is necessary to develop the intuition of the general public in understanding complex systems.

- **Final comments**

The Newtonian deterministic approach is somewhat limited when investigating complex systems. Therefore, we need to accept a new direction, a probabilistic approach.

6. Perspective of Janos Kertesz

Janos Kertesz[1,2,3]

[1]Central European University, Austria
[2]Complexity Science Hub Vienna, Austria
[3]European Center for Living Technologies, Italy

- **Defining complex systems**

It is no accident that the definition of complexity has not become consensual [26]; this is rooted in the very nature of the subject. Complexity is ubiquitous so that the formulation should be very general, while the variability of the related systems is extremely large. In fact, much of the history of science is about fight against complexity: trying to find and understand phenomena, which are not complex and isolating systems such that a non-complexity approach can be applied. The amazing success of that approach is due to the separation of scales—a feature usually missing in complex systems.

Rather than trying to define what a complex system is, in my course I usually list properties (many interacting constituents, collectivity, nonlinearity, feedback mechanisms, emergent phenomena) that are always, and properties (hierarchical organization, ordering, adaptivity) that are often present in them, and I make clear the difference between complicated and complex systems.

- **Biggest challenges in the next twenty years**

Challenges will be in both fundamental complexity science and its applications. In the following I will flash some examples going from basic to applied problems.

Many real complex, far from equilibrium systems are unique, i.e., there is one history (and future) of a such system and that's all. Examples include biological evolution, human history, dynamics of the economy, etc. Stuart Kauffman's pioneering work [27] on the 'adjacent possible' is an important development in this context and much more is to be expected. For such systems the basic concept of statistical physics, that of ensembles is hardly applicable and even the question about self-averaging makes little sense. Instabilities on all scales and rare events induce very different histories and only one of them is of relevance. There are conceptual challenges related to this fundamental problem.

Much effort has been paid to uncover the relationship between function and topology of complex systems, but we are far from a systematic understanding. In recent years the toolbox of network science has developed tremendously by including multi-layer and higher order networks into its scope [14, 28, 29], which will trigger research further in this direction. Likewise, a major challenge of the near future will be the identification of the effects due to the physicality of the connections and the related excluded volume effect in some complex systems leading to 'physical networks' (e.g., the brain or molecular networks) [30].

Complex systems involving humans are particularly challenging due to the role of consciousness in adaptivity. Yet a further level of complexity is to be expected when AI comes into play. There is a strong and justified tendency towards a paradigm change in AI from centrally controlled to distributed realizations to achieve explainability, assure privacy and individual control of personal data [31]. In such a complex ecosystem of humans and AI, unexpected emergent phenomena will show up and their understanding and possible control will be crucial for the smooth operation.

Our world is full of severe problems related to complex systems; war, pandemics, financial crises, climate change, increasing inequalities and crime are just a few examples. I think (and hope) that the role of complexity science in decision making will increase—the understanding of complexity scientists is rather incomplete, but still, in many cases they are, who understand most. The handling of Covid-19 in some countries provide encouraging examples in this regard. It is among the biggest challenges for complexity science and the responsibility of complexity scientists to push forward this process and to focus on the understanding of the above and similar problems, to make the results publicly accessible and come up with suggestions and scenarios for possible solutions.

- **Implications of the 2021 Nobel Prize**

The work of the Nobel laureates has shaped our understanding of complex systems in many ways. Syukuro Manabe and Klaus Hasselmann have demonstrated that physical insight combined with advanced numerical techniques provide understanding of complex systems and lead to solid results like in the case of global warming. The long overdue award to Giorgio Parisi celebrates his many contributions including the concepts of scaling and multiple optima in disordered systems [32–34]. A Nobel Prize always gives a push to the scientific field which the awardees are active on, and this should be the case for complexity science too. However, the impact of the Nobel Prize on research is mostly secondary: there is some public attention turning to the field, decision makers get some impulse, etc. There is already a sign for the latter in Italy where some changes in the funding practice have been announced. Such a move should naturally have an effect on research. I hope that other countries will follow Italy, even without having their citizen among the laureates. Perhaps changes will happen at European level too, which would be most desirable as complexity is typically a field where there is much room for collaboration over the boarders. The Nobel Prize may also have an impact on university curricula attracting more students to this fascinating field.

- **Robustness and fragility of complex systems**

Complex systems mostly result from evolution; therefore, they must have some level of robustness—otherwise we would not see them. The diversity of such systems, however, is also reflected in the fact that some of them are very robust while others are more vulnerable. A good example for the former is scale free networks' robustness against random failures, however, coupling of such systems like in the case of interdependent networks may lead to an enhanced vulnerability [9, 35].

Robustness of a system may stem from being locked into a metastable state and only sufficient strength of fluctuations or perturbations can forced it find another state of operation. An example from a recent study from social systems shows how network structure representing social capital in a town can impact and lock in corruption risk, providing an explanation to the persistence of thereof [36].

- **Prediction in/with complexity**

Already in low dimensional chaos (which should not be considered as complex in the above sense) predictability is a difficult issue. In complex systems this is even more the case due to the heterogeneity often present on all scales, the different kinds of nonlinearities and instabilities and the diversity of noises and external perturbations.

For the above-mentioned unique, 'single history' systems predictability is extremely difficult as occasionally one unexpected event may radically change the trajectory of the system so that 'learning from the history' becomes difficult or impossible. The time span of the predictions is very limited as the probability distributions change abruptly at such an event—moreover the meaning of probabilities becomes obscure for such systems.

In spite of these difficulties there are success stories—the best example is the prediction on the spreading of diseases, where, as a result of interdisciplinary effort and usage of Big Data, real-time simulation and short-term accurate predictions are available [37]. Due to the Covid pandemic these techniques have found rapidly their way to assist decision making.

- **Advantages and challenges of interdisciplinary research**

Interdisciplinarity is inevitable in the study of complex systems. The difficulties are obvious: finding the common language is the lesser one—finding the appropriate, open-minded colleagues with whom a synergic cooperation is possible is usually the real challenge. Fortunately, there is an increasing number of researchers, who do not consider complexity scientists as intruders to their fields but recognize that many of the burning problems in science and its applications call for new approaches and interdisciplinary cooperation.

7. Perspective of Jürgen Kurths

Jürgen Kurths[1,2]

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• **Defining complex systems**

In the beginning, two-three decades ago, complex systems were considered as some counterpart to complicated systems and hence often referred to rather low-dimensional systems. There complexity arises due to complex interactions. This has been extended now clearly, and mostly we study high-dimensional systems, in particular systems composed of many components, with complex interactions and call them complex systems. This has enabled us to analyze important real systems as brain, finances, climate or power grids.

• **Biggest challenges in the next twenty years**

We strongly need to develop theories and corresponding techniques to treat large coupled heterogeneous systems which are evolving in time and space and are influenced by perturbations of broad variety, not restricted to Gaussian processes and small intensity. This requires real interdisciplinary methodological approaches including especially statistical physics, graph theory, stochastics, mathematical statistics, machine learning, nonlinear dynamics and nonlinear data analysis. This way we will be able to treat challenging problems in the real world of the next two decades, e.g. modelling of system Earth by including manifold natural components as well as human influences and all their interactions, studying the cyberspace and its relations to infrastructure, spreading of diseases etc.

• **Implications of the 2021 Nobel Prize**

Here, for the first time, both complex systems science and climatology were recognized as substantial parts of physics, a huge success after more than 100 years research in both fields. Note the following milestones combining physics and climatology: Svante Arrhenius found that greenhouse gases induce a temperature increase [38], Vilhelm Bjerkness used basic physics equations for weather prediction [39] and Lewis Fry Richardson wrote his seminal book weather prediction by numerical process [40].

• **Robustness and fragility of complex systems**

Mostly the classic and highly successful concept of Lyapunov stability has been used in complex systems science, i.e. mostly local influences of small perturbations have been analyzed. However, real systems often undergo non-small perturbations. Therefore, many recent theoretical results are not so useful for evaluating robustness and fragility of real-world systems. The development of more general concepts for robustness and fragility investigations is therefore a challenging problem.

• **Prediction in/with complexity**

Complex systems science could provide efficient techniques for predictions of various systems, which go substantially beyond known methods. One direction are early predictions of critical transitions or tipping points, another one is to construct rather medium- or even long-time forecasts of rather stationary complex dynamics, where we know that very long-time predictions are impossible and a further is to calculate scenarios for future dynamics under evolving conditions. An outstanding example for the latter one are Hasselmann's and Manabe's studies on the influence of carbon dioxide increase on increasing global temperature already in the 1980ies [4, 41–43].

• **Advantages and challenges of interdisciplinary research**

Complex network science has been interdisciplinary from the very beginning on. Its main achievements have been reached, when interdisciplinary teams have formed and really collaborated. The future challenges require even stronger interdisciplinary approaches.

• **Final comments**

I am indeed happy to be part of this community, I mean all scientists working in complex systems science. It is such an active field and many positive surprises have occurred in its rather short history; and I expect many more. I have always enjoyed the special constructive and friendly atmosphere of this community. We should always have in mind that our subject are OPEN systems and we should strongly keep the open nature of our interdisciplinary work over all continents of our Earth and we should NEVER follow restrictions on this collaboration dictated by politicians and other general decision makers.

8. Perspective of Linyuan Lü

Linyuan Lü

University of Electronic Science and Technology of China, People's Republic of China

• **Defining complex systems**

Complex systems are formed by many agents interacting with each other in nonlinear ways, thus yielding complex phenomena that cannot emerge from the simple sum of the agents. Complex systems have commonalities that can be modeled and researched.

For example, an airplane has tens of millions of parts, but as long as we understand the function of each part, we can understand how it flies. While for our brain, even if we understand how each neuron works, we still do not know how consciousness and intelligence emerge. Thus, systems that can be understood in disassembly (by means of reductionism), where the whole is equal to the sum of the parts, are complicated, but they are not the complex systems investigated in complexity science. Systems like the brain, where the functions and properties of the whole part are not linear sums of parts, are the complex systems we are really interested in. As with flocks of birds, the flight of a single bird is a mechanical problem, while the flight of a flock of birds is a matter of complexity science.

- **Biggest challenges in the next twenty years**

Exploring the underlying mechanisms of complex systems is a long-term challenge for complexity science study. With the rapid increase in data availability, handling large-scale heterogeneous (noisy) data and modelling it as dynamic systems are also important challenges for complexity science in the future. To be more specific, some challenges include:

∗ How to go beyond correlations and address causality in complex systems is a recent focus of researchers in the field for which new methods have been proposed recently.

∗ The brain is the most paradigmatic example of a complex system, a significant challenge is understanding its functioning from the perspective of complexity science. This research will contribute to solving (or at least will advance the research of) many fundamental questions that are still open in brain research, such as the relation between the structure of neural circuits and their function, or the interplay between the structure of brain networks, disease, and cognition.

∗ How to analyze complex systems beyond pairwise interactions is fundamental to better understand complex systems. To name just a few, challenges related to higher-order interactions: (a) identify, quantify and reconstruct the higher-order interactions (and the higher-order structure) from data; (b) explore the basic principles of the emergence of complex dynamics in systems with higher-order interactions; (c) investigate the evolution and regulation of complex systems' function from the perspective of high-order interactions.

∗ How to combine network science with artificial intelligence to put forward better theories and methods and solve practical problems.

∗ How to utilize well the theory and methods of complexity science by integrating them with large-scale real-world data in order to improve every aspect of human life and support good government policies.

- **Implications of the 2021 Nobel Prize**

It is the first time that the Nobel Prize in Physics was explicitly awarded for the research in complex systems, which is a remarkable milestone. The importance and contribution of complex systems science is acknowledged with the highest award in the natural sciences. I believe the 2021 Nobel Prize will promote the flourishing of complexity science, whose theory and methodology will be more extensively applied and developed by researchers from various fields. In 2000, Stephen Hawking said 'I think the next century will be the century of complexity'. Yes, he was right!

- **Robustness and fragility of complex systems**

Complex systems are mix of order and disorder, and this is just where the complexity of systems lies. The agents in the complex systems interact with each other in a disordered way, and the order of a complex system may arise from the disorder of the interactions. The order is robust under perturbations. At the same time, complex systems are highly flexible, the evolution of which is sensitive to diverse conditions. The optimal state of a system might be to maintain a dynamic equilibrium. From this perspective, I think that defining simple rules behind this mechanism and predicting the future evolution of complex systems are two of the key problems that will shed light on this interplay.

- **Prediction in/with complexity**

Complex systems are highly dynamic and sensitive, we cannot expect specific and accurate predictions of what will actually happen. The best we can expect is predicting the probability that something will happen (similar to a weather forecast). This is not because of the lack of information, but because even a tiny fluctuation in a complex system can be magnified to produce unpredictable outcomes (e.g., the butterfly effect, chaos…). While for events with stable patterns, as long as we can collect enough data of the past, we can predict the probabilities of events that will occur. For example, by analyzing the characteristics of users' behaviors on the internet, we can do a good job in recommending content (such as short videos, news, books, and products) he/she will be interested in. Interested readers can refer to the book *Everything is Obvious* by Duncan J Watts [44] for more examples (the Chinese translation of this book is entitled 反常识). Common sense can be very successful and effective when dealing with simple problems, but it has a high probability of failure when applied to complex problems (in complexity science). So for complex problems, the experience of past success is actually very limited or even plays a negative effect (e.g., the Black Swan).

- **Advantages and challenges of interdisciplinary research**

Understanding complex systems requires interdisciplinary study. Complexity science integrates the insights coming from different disciplines into a comprehensive understanding, and allows us to further develop methods with general applicability. For example, we can use the knowledge in physics to identify patterns and address problems we confront in society. So, the main challenge is figuring out which discipline and perspective can contribute to the understanding of the target system we study. For multiple complex systems, the problems that arise are interdisciplinary problems, i.e. problems beyond the realm of a single discipline, and they require an interdisciplinary approach. An important issue is how to strengthen multi-disciplinary cooperation. From the perspective of education, some educational reforms are needed. How to train students for interdisciplinary research in complexity science? I believe that it could be beneficial to add courses and practices in complex systems research to the curriculum of various disciplines.

- **Final comments**

The researchers of complexity science all over the world are in a community with a shared future. We should strengthen ties and cooperation to advance the development of complexity science and its possible contribution to other important areas regarding human survival and development.

9. Perspective of Cristina Masoller

Cristina Masoller

Universitat Politecnica de Catalunya, Spain

- **Defining complex systems**

A main requirement of a complex system is that it has large number of interdependent variables and/or it is composed by a large number of interacting elements. In other words, a complex system has a high dimensional phase space. How large? It depends but I would say that a complex system has at least about 10 elements/variables. A second key requirement is that the system is nonlinear (the elements, the interactions, or both are nonlinear). A third condition is that the structure of the system is heterogeneous (in other words, the interactions are not fully regular neither they are fully random). A large linear system is 'complicated', while a large nonlinear system is complex.

A typical property of a complex system is that the system's response to a perturbation is nontrivial and often contra intuitive and unexpected. In other words, the behavior of a complex system is very difficult to forecast and to control. Linear techniques such as interpolation and extrapolation may fail to predict the behavior of a complex system. Reductionism (quoting from Wikipedia 'as an intellectual and philosophical position that interprets a complex system as the sum of its parts') also fails due to the nonlinear nature of the elements and/or the interactions present in the system.

Other characteristics of complex systems are:

* They are usually multiscale, in space, in time, or both;
* They have memory: due to delays in the interactions and feedback loops, the future state of a complex system usually depends on its present state, and also, on the past of the system.
* They are often characterized by non-Gaussian statistics, and can show extreme and/or rare fluctuations. What do we mean by extreme fluctuation or a rare event, in the context of a complex system? A precise definition, of course, depends on the particular system, but in general terms, we may argue that a fluctuation might be very large, but not extreme in the sense that it will not have a long-term impact (as the system can be robust against some very large fluctuations and will shortly after return to the previous state). In contrast, an extreme fluctuation (not necessarily very large) or a rare event may produce a long-term impact in the afterward behavior of the system, that might even undergo an irreversible transition to a different state.
* Multistability is also a common characteristic of complex systems as these can display abrupt changes, i.e., transitions to different states and, in the presence of drifting or time-varying parameters, hysteresis phenomena.
* When a complex system has many interactions and feedback loops with time delays, it can also show very long transients before reaching a stationary state.

- **Biggest challenges in the next twenty years**

In my opinion one of the biggest challenges is related to the spreading of information in our societies. How can we use social media and complexity science (CS) to fight disinformation, to stop fake news and to promote cooperation? CS has generated detailed models on rumor speeding in complex networks, and we need to know how to use this knowledge in real situations. For instance, how to exploit social networks (Facebook, WhatsApp, Instagram, Twitter, etc) to promote cooperation, and to stop the spreading of fake news that are generating a strong polarization in our societies (e.g. Brexit, the growth of ultra-right political parties, animosity against minorities, immigrants, etc).

- **Implications of the 2021 Nobel Prize**

The Physics Nobel Prize 2021 recognizes the importance of inter-disciplinary research. Climate change is another important challenge of complexity science (how to make people aware of the problem, that needs coordinated efforts now, not only by governments, but also, by each of us). The Nobel Prize 2021 recognizes that research in climate modelling and nonlinear methods allow us to understand our climate and to predict dangerous changes in the climate due the increase of CO_2 in the atmosphere produced by human activities.

- **Robustness and fragility of complex systems**

Because of nonlinearities and feedback loops, complex systems respond to perturbations in a way that is usually unexpected and often, contra-intuitive. Complex systems are constituted by a large set of diverse elements that play different roles in the structure and functioning of the system, and this means that there are some elements that can be crucial for propagating critical information, for synchronizing the system, for generating dangerous fluctuations, etc. Therefore, while a complex system can be very robust against generic perturbations, it can be very fragile against targeted perturbations to particular elements, that can produce a cascade or an avalanche of critical failures.

- **Prediction in/with complexity**

The prediction of the behavior of a complex system is challenging because of the three characteristics of a complex system: very large size, nonlinearity and heterogeneity. The equations that describe a complex system have a huge number of variables and parameters and therefore, if we want to use machine learning (ML) for prediction, the training is very demanding, both, in terms of data requirements and in terms of computing power. One may hope that, with large enough computing power, the output of a ML algorithm will approach the true dynamics of a complex system in the 'thermodynamic limit' of past observations. However, because complex systems are often non-stationary (and may display very long transients and abrupt transitions), even if we have very long observations (of all the system's variables, with high temporal resolution) we may still be unable to predict, with a good level of confidence, the future state of the system.

To understand and to predict a real-world complex system, interdisciplinary efforts are usually needed. In my opinion, a success story is the use of complex networks and nonlinear data analysis tools to advance the understanding of the dynamics of our climate, and to uncover subtle causal effects which cannot be detected by conventional (linear) techniques. I refer the interested reader to the references [45, 46].

- **Advantages and challenges of interdisciplinary research**

Progress needs cooperation and the main advantage of interdisciplinary research is that it can produce significant progress. As an example, one can simulate very detailed climate models and also analyze observational climatological data, but without the direct involvement of experts in weather and climate in the research, the information obtained from models and data analysis cannot advance our understanding of the underlying physical processes.

A main challenge of interdisciplinary research is to encourage researchers in different disciplines to talk to each other and to try to understand each other's needs and interests. It is a big effort for all parts to move 'out of the comfort zone' and try to understand each other, but there is a lot to gain, as genuine progress can only be achieved by joining efforts in different disciplines. As an example, I mention the development of photonic artificial intelligent (AI) systems using photonic neurons: by using laser light we can develop much faster and more energy efficient AI systems, but to use 'photonic neurons' that genuinely mimic biological neurons, we need to understand neural dynamics and we also need to understand how to implement in photonic systems the nonlinear mechanisms by which neurons encode and process information.

To promote interdisciplinary research, there is the need of interdisciplinary scientific events that bring together experts from different fields (it is unlikely to find a neuroscientist in a photonics conference, and vice versa; as an example, scientific events such as the workshop in 'Computational Neuroscience and Optical Dynamics' that was held a few years ago in Nice, are needed for promoting interdisciplinary discussions). Also crucial are the existence of interdisciplinary panels in the calls of funding agencies, which are nowadays typically organized in well-delimited areas such as physics and math, biology and medicine, social sciences and humanities.

• **Final comments**

Interdisciplinary research has finally received the recognition it deserves. Interdisciplinary research is, in my opinion, the only way to address the most important challenges of our societies in the next years (climate change, health and life style of the aging population, fake news and societal polarization, etc).

10. Perspective of Adilson E Motter

Adilson E Motter

Northwestern University, United States of America

• **Defining complex systems**

I appreciate that many researchers prefer to define complex systems in terms of attributes they often exhibit, but I tend to favor a definition based on their fundamental nature. Accordingly, I take a complex system to be a system that (i) is made up of interacting component parts and (ii) exhibits dynamical behavior that cannot be inferred from the behavior of the parts themselves. In such systems, the interactions between the parts can be as important as the parts themselves in determining collective behavior. As per this definition, complex systems lend themselves naturally to be modeled as networks of interactions. In particular, the control of such systems can in principle be based on tuning the parts or the interactions between them [47].

It is possible for a system consisting of only two entities to exhibit emergent behavior and thus complexity, as in the synchronization of a pair of coupled metronomes. Likewise, it is possible for a system with regular structure and identical parts to exhibit emergent properties (e.g., diamond vs graphite), as indeed considered in major areas of condensed matter physics. That said, it is often the case that complexity science researchers are interested in systems consisting of a large number of interacting components, and I see no harm in allowing that to be part of the definition. They are also often interested in systems that are disordered and/or heterogeneous, and thus systems whose structure itself is also 'complex'. The network of interactions can be rather general, and may not be limited to being local or naturally represented in an ordinary physical space. In that sense, I would regard the current study of complex physical systems as a form of 'post-condensed matter' physics.

• **Biggest challenges in the next twenty years**

There are both scientific and structural challenges. A major scientific challenge is to move from the simple models that dominate many subfields to realistic models that can be validated against data. Models have to be taken with a grain of salt in every area of science, but this is especially the case when dealing with complex systems due to the richness of details, the need for holistic approaches, and the frequent adoption of coarse-grained descriptions. In this context, other hurdles to be overcome include strengthening connections with experiments and ensuring the quality of the data used.

Complexity science also faces structural challenges due to its interdisciplinarity. Much of the current research on complex systems is pursued under numerous others designations, from systems biology to computational social science. Conversely, self-identified complex systems researchers often work on sufficiently distant topics that they may not be familiar with each other's system. As the field matures, a challenge is thus to define its identity and scope beyond the existing niches delineated by specific conferences, journals, and societies.

• **Implications of the 2021 Nobel Prize**

By honoring work that is very much built on data-based modelling and work in the well-established area of statistical physics, the 2021 Physics Nobel Prize budges the needle on the two challenges identified above. In particular, it contributes to defining the scope of the field within physics, which promises to influence personnel training, recruiting, and the creation of new programs. While the impact is most immediate in physics, the highly multidisciplinary ramifications of the awarded research suggest that the prize may also have implications for a number of other disciplines.

• **Robustness and fragility of complex systems**

I would start with a brief comment on the promise of the question. Many real systems are selected for robustness and they tend to involve interactions. As a result, they tend to be complex and robust. While this co-evolution of complexity and robustness is common, it is not difficult to conceive complex systems that are not robust. Response to perturbations is an important question for most systems, complex or not, and even if they are generally robust. However, when the system is complex, the realm of possible responses seems richer.

In the study of perturbation responses, the network representation of complex systems can be especially insightful, since perturbations in such systems often do propagate through networks. This leads to numerous fundamental questions, which form the basis of much of my own research [48, 49]. When does a local perturbation have global impacts? When can the perturbation to one system impact a coupled interdependent system? How can seemingly indistinguishable perturbations have dramatically different consequences? How to predict extreme but rare events and account for uncertainty? How to control the response of a complex system to perturbations? The latter is all the most important given that many complex systems of scientific interest evolve and function in a decentralized manner.

- **Prediction in/with complexity**

Prediction is challenging because of high dimensionality, nonlinearity, and uncertainties. These features are not unique to complex systems, but they can be more consequential in this context. This is so because complex systems cannot, by their very nature, be explored using purely reductionist approaches, and the development of system-wide dimension reduction methods that can be broadly applied remains work in progress [50].

It is also instructive to reflect on success stories. For those of us with background in chaos, the remarkable advance in weather prediction is an example that stands out. From the complexity science perspective, this advance appears to derive from considerable progress made in understanding the weather system in the first place. It could therefore be argued that to improve our ability to predict the behavior of other complex systems we have to first improve our understanding of the principles governing such systems. This may, in particular, open new opportunities for hybrid approaches combining machine-learning and knowledge-based models [51].

- **Advantages and challenges of interdisciplinary research**

The advantages are that insights, methods, and even phenomena transfer from an application field to another. As a consequence, discoveries can have far reaching implications. Personally, I also appreciate the freedom to explore the consequences of my research in disparate problems and I believe this feeling is shared by many colleagues. The most immediate challenge is the difficulty to form a cohesive research community.

- **Final comments**

This is not the first time that complexity science is the subject of a Nobel Prize. In physics, previous examples include Nobel prizes in statistical physics, such as the 1977 prize awarded to Philip W Anderson, Sir Nevill F Mott and John H Van Vleck '*for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems*'. Other instances can be found in chemistry, such as the prize awarded the same year to Ilya Prigogine '*for his contributions to non-equilibrium thermodynamics, particularly the theory of dissipative structures*' and, more recently, in 2013, the prize awarded to Martin Karplus, Michael Levitt and Arieh Warshel '*for the development of multiscale models for complex chemical systems*'. The are also prominent examples among the Nobel Memorial Prizes in Economic Sciences, including the 1978 prize awarded to Herbert A Simon '*for his pioneering research into the decision-making process within economic organizations*' and the 1994 prize awarded to John C Harsanyi, John F Nash Jr and Reinhard Selten '*for their pioneering analysis of equilibria in the theory of non-cooperative games*'. However, none of this reduces the historical significance of the 2021 Physics Nobel Prize '*for groundbreaking contributions to our understanding of complex (physical) systems*', given the much reported fact that the rationale for this prize involved a broader and more explicit reference to complex systems than any previous one.

11. Perspective of Matjaž Perc

Matjaž Perc[1,2,3,4]

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[2]China Medical University, Taiwan
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[4]Complexity Science Hub Vienna, Austria

- **Defining complex systems**

A complex system consists of a large number of relatively simple units, which collectively display complex behavior. Much more complex than one could ever imagine given the simple building blocks that make it up. And it is really the story of life, from the cells in our bodies, to the ants in anthills, to the zeros and ones that make the entirety of our digital existence, to humans in societies, and to the planets and stars that form the Universe. Complex systems span the entirety of our existence, and they might be the very fabric of life.

- **Biggest challenges in the next twenty years**

Complexity science is everywhere, but also nowhere in that it hardly exists without the context of another field of science. Be it physics, or chemistry, or biology, or sociology, or economy; examples of complex systems abound in all these fields, but as a field itself, complexity science is quite notoriously difficult to define in its own right. And this is certainly a challenge—how do we then argue in favor of applicability, and importance, and relevance, and the need for funding, if the very existence of complexity science is contingent upon other fields. The biggest challenge might be to truly grasp the vastness and the overarching importance of complexity science, and as soon as we do so, to provide the fundamentals and the context for the field to stand on its own right.

- **Implications of the 2021 Nobel Prize**

It is a much needed, and perhaps also an overdue, recognition that will stand out in the history of the field as an important milestone toward its maturity and even wider appeal.

- **Robustness and fragility of complex systems**

When we discuss the robustness and the fragility of complex systems, it is important to understand that both can easily coexist, and that the two concepts are not contradictory per se. Complex systems are robust as long as they are not close to a phase transition or a tipping point, beyond which changes are often abrupt and irreversible. The climate of our planet Earth is a beautiful example of this very fact. The Holocene is the name given to the last 11 700 years of the Earth's history, during which we have witnessed quite amazing robustness of the conditions in which we live. And this robustness has allowed for the evolution of the lives that we now live, from farming to agriculture, to progress in science. But we want too much, and we exploit and we harvest and we burn the natural resources at a ferocious pace. A pace so fast, that we have pushed the climate very near a tipping point. If the complex system that is our climate system would not be robust, the Holocene might have ended already 10 000 years ago. But it did not. It took extreme behavior on our end to push this complex system to the breaking point. And it is precisely the complexity science that enables us to understand and to communicate this so well now, both to ourselves, the scientists, and to the general public. The rubber band analogy might be well in order: a complex system is likely a very robust and hard rubber band. One can pull so hard on it, and it may always return right back to its original shape. That is, until one pulls too hard. Then it will snap and move in the most unpredictable and largely irreversible and irreparable ways.

- **Prediction in/with complexity**

Prediction of anything meaningful and not obvious is always challenging. In this light one may rephrase the question and ask whether it might be that nonlinear and complex systems are indeed the only ones worth bothering with in terms of prediction? And the answer would be yes, and the challenge itself would be just an obvious consequence of the fact that were prediction not challenging, life itself would be boring and predictable. Any success stories we have are probably lucky strikes in that the complex systems we successfully predicted operated far away from tipping points. But where is the fun and the success in that? The real thing is, probably thankfully so, inherently unpredictable.

- **Advantages and challenges of interdisciplinary research**

Interdisciplinarity is both a blessing and a curse. It is a blessing because it is widely and generally applicable, and one can explore many fields if one masters well the fundamentals of complexity science. And it is a curse because whatever one does, and no matter how successful one is, the home is missing. Or at least, it is still heavily under construction. And this inevitably still creates challenges in recognition, in funding, and ultimately in career prospects. Things are improving, but we have generations lost to the lack of opportunities for stable research careers in complexity science.

- **Final comments**

Warmest congratulations and thanks to Giorgio Parisi for his groundbreaking discoveries that have made what we do now possible.

12. Perspective of Filippo Radicchi

Filippo Radicchi

Indiana University, United States of America

- **Defining complex systems**

A system is complex when its behavior is characterized by the superposition of multiple, structural and/or dynamical, scales. Complex behavior in a system generally emerges from the interaction of many elementary objects. Examples of complex systems can be found anywhere in nature, including social, biological, and technological systems.

- **Biggest challenges in the next twenty years**

I see a tight connection between data science and complexity science. As more and more data about real complex systems become available, novel challenges for complexity science emerge. In a such fast-evolving scenario, it is difficult to predict specific problems that will be considered in next twenty years of research. However, I expect that the biggest contributions of complexity science will regard complex socio-technical, biological and climate systems.

- **Implications of the 2021 Nobel Prize**

The Nobel Prize assigned for discoveries in complexity science represents an important recognition to the entire field of research. I hope it will stimulate further investments in the field and will open new possibilities for important discoveries in the years to come. The award is very timely. The increasing availability of data describing real complex systems and the emergence of new types of real complex systems (e.g., social media) is generating theoretical challenges for complexity science that were not even possible to conceptualize a few years ago.

- **Robustness and fragility of complex systems**

A system can be robust under some conditions but become fragile under other conditions. A celebrated theoretical result in network science is quite representative in this regard. Complex networks are robust to random perturbations, but they display extreme fragility to targeted attacks.

- **Prediction in/with complexity**

The superposition of multiple scales in complex systems naturally leads to difficulties of making accurate predictions. Additional challenges may emerge in the prediction of dynamical properties because of the non-linearity and chaotic nature of the dynamics that often characterizes complex systems. There are, however, some success stories of predicting the behavior of complex dynamical systems. The analysis of contagion models on complex network topologies for example allows for quite accurate predictions of disease spreading in the real world. Also, percolation theory applied to networks provides with very accurate estimates of network robustness to random and/or targeted damage.

- **Advantages and challenges of interdisciplinary research**

The biggest challenge is represented by potential communication barriers that may be present at various levels. For example, there are only a few conferences/journals that are dedicated to interdisciplinary research in complex systems. On the other hand, many important scientific problems can be faced only by truly interdisciplinary teams of research. So, if the above-mentioned communication barriers are surpassed, then an interdisciplinary collaboration may lead to a groundbreaking discovery.

13. Perspective of Ramakrishna Ramaswamy

Ramakrishna Ramaswamy

Indian Institute of Technology-Delhi, India

- **Defining complex systems**

Any physical system wherein the reductionist approach is fundamentally wanting is in some sense a complex system. I kind of like the Parisi definition (I heard this in a talk by Virasoro many years ago) that ‘the more you can talk about a system, the more complex it is’. Of course this can be made quantitative, but the statement captures the main feature of complex systems, that to be described they need many degrees of freedom, many variables.

- **Biggest challenges in the next twenty years**

As of now it seems that there is a set of paradigms, examples of systems that are complex and examples of systems that are not. Notions of emergence and collective behavior are important, but these need to be made quantitative. A proper classification of types of complexity, the systematics that is characteristic of a discipline is still a major challenge, and one that will occupy us in the area of complex systems in the coming years.

14. Perspective of Francisco A Rodrigues

Francisco A Rodrigues

University of São Paulo, Brazil

- **Defining complex systems**

I think complexity is mainly related to the phenomena of emergence and collective dynamics. If we consider its traditional definition, in which a complex system is made of interconnected parts, we can say that a car or a machine is a complex system. However, a vehicle is only a complicated system in which we know how each part works. Unlike a car, we can observe a high tolerance to failures in complex systems, where the system reorganizes its structure and dynamics according to an external perturbation. In a complicated system, like a car or a computer, we do not have these tolerance mechanisms to failures—the system does not adapt to the changes in the environment. Complex systems adapt to the changes occurring in the environment and maximize the information flow among its components. Moreover, complex systems present emergent phenomena. Our memory in our brain or the cooperation between termites in a nest are examples of emergencies. These systems do not present a central control, and the system dynamics are the product of the interacting elements. Thus, in my opinion, to define a system as a complex system, we have to consider these collective dynamics and the emergence property.

- **Biggest challenges in the next twenty years**

The biggest challenge in modelling complex systems today is the lack of accurate data. For example, we have many data about static networks, like roads and the links between routers on the Internet, but there is little data on temporal and multilayer interactions. Temporal networks are essential to study dynamic processes, like an epidemic spreading, which depends on the connections between people throughout the day. Temporal networks are also essential to studying interactions between species, social contacts and genetic networks. On the other hand, multilayer networks are made of interconnected networks. These networks are fundamental to understanding biological processes, which are composed of several levels—genetic interactions are influenced by protein–protein connections, which are defined by metabolic reactions, and vice versa. Therefore, an essential challenge in complexity science is how to get more accurate data about our world that consider not only spatial but also real-time data.

- **Implications of the 2021 Nobel Prize**

The Nobel Prize 'for their groundbreaking contributions to the understanding of complex physical systems' was a considerable contribution to complexity science. Mainly, Giorgio Parisi has studied spin glasses, i.e., disordered magnetic systems, and developed mathematical tools employed in studying complex systems. The recognition given by the physics community shows the importance of complex systems for the progress of humanity. Physics is no longer looking only at the micro (quantum world) or macro (astronomy) but also at our scale, where the main problems of humanity are, including global warming, epidemics, social inequality and wars. All these applications can be studied using complexity theory. Therefore, when Stephen Hawking stated in 2000 that the twenty-first century would be the century of complexity, he was right.

- **Robustness and fragility of complex systems**

Complex systems are known to be robust, mainly to random failures, due to the scale-free organization of the underlying networks. However, resilience is not enough to keep the system working. It is essential to have a network structure in which the information flow is also optimal. Therefore, a fundamental problem to be studied nowadays is understanding how robustness and navigability are optimized simultaneously in a network—other dynamic properties can also be considered, like the synchronization in our brain. Moreover, most works consider the resilience against random removal of nodes as a measure of robustness, but other types of resilience should be considered. For instance, robustness can quantify how efficiently a system synchronizes or how easy players cooperate. Suppose some perturbations are inserted in the system, such as an oscillator with a very different natural frequency or a player who copies their opponents' strategy. In these cases, such changes will not significantly affect a robust system. Therefore, there are other ways to define resilience, and the theoretical formulation of this concept is a challenge in complexity science.

- **Prediction in/with complexity**

Prediction is fundamental in many applications of complexity science. However, this task is challenging since complex systems present nonlinear dynamics, feedback, and interactions between elements, making these systems hard to predict using the current tools from statistics and machine learning. Indeed, most inferential methods assume that the observations are independent and their properties are static, keeping the same probability distribution with time. However, complex systems present elements that interact nonlinearly, showing feedback and influencing each other. Therefore, traditional methods to predict the system's evolution are unsuitable, providing poor forecasting in many applications. One way to overcome these limitations is to use deep neural networks, which are suitable for nonlinear data. However, when using neural networks, we gain in prediction, but we lose in interpretability since these neural networks act as black boxes in the forecasting process. Thus, a challenge today is making these neural networks more interpretable, which will help understand how the organization and evolution of complex systems affect their dynamics. Another critical issue regarding forecasting is the so-called 'context changing'. For instance, when predicting the number of cases of SARS-Cov2, most models could not provide an accurate prediction in the begging of the pandemics due to the lack of data. Later, when we had more data, the prediction was inaccurate because the prediction results changed the system's behavior. When people verified an increase in cases, they started to protect themselves, and many governments adopted lockdown policies, influencing the transmission dynamics. Therefore, previous data was no longer suitable since the same equations no longer govern the system's evolution. Unfortunately, in most complex systems, this change of dynamic behavior due to interventions is ubiquitous. When we use some new drugs for cancer treatment, these drugs can change the evolution of the disease. At the same time, when we try to block the propagation of fake news on social media, this blocking can generate new social movements, improving the propagation. Therefore, forecasting in complex systems is a big challenge that will be addressed only with new theoretical methods since the traditional techniques cannot predict the complex dynamics observed in most real-world systems.

- **Advantages and challenges of interdisciplinary research**

The main advantage of being interdisciplinary is that complexity science can join different research fields. Complexity science enables scientists from different disciplines to talk and collaborate on fundamental problems for our society. Differently from other areas, which are very specialized, complexity permits the integration of different disciplines, enabling the knowledge to evolve uniquely. The interdisciplinary research will address the main problems of humanity, including global warming and the emergence of pandemics, poverty and wars. Therefore, interdisciplinary is one of the main attributes that make complexity science essential and recognized today.

- **Final comments**

The Nobel Prize 2021 is a recognition that physics is not only interested in questions related to the origin and evolution of the Universe but also to the present time in order to improve people's lives. Understanding complex systems is fundamental if we tackle humanity's main problems and plan our future in a sustainable, increasingly healthy and humane way, with assistance for everyone, without exhausting our planet.

15. Perspective of Marta Sales-Pardo

Marta Sales-Pardo

Univ Rovira i Virgili, Spain

- **Defining complex systems**

Systems composed of many interacting units (usually in a non-linear fashion) whose macroscopic behavior cannot be explained by the behavior of individual components.

- **Biggest challenges in the next twenty years**

I think that there will be many challenges associated to data, modelling data and in how to communicate our results to society and policy makers, in general. The recent pandemic has shown that uncertainty is a hard concept to grasp for the general society, our challenge will be to make this concept clear in a variety of contexts. For complex systems science, our goal will be to better understand and (if we can) find ways to tame or reduce uncertainty. In this directions, I think that artificial intelligence tools, if used in a meaningful, controlled way can be very powerful. A challenge for complex systems scientists will be to harness the power of AI tools (which are able to deal with lots of data) for the understanding of physical systems. This will require going beyond the current black-box, predictive tools we have come to know until now and develop new AI tools that are suitable for the properties of the kinds of complex systems we want to study.

- **Implications of the 2021 Nobel Prize**

As a person who did her PhD in spin glasses, I think that the Nobel Prize awarded to Giorgio Parisi is a recognition, not only to his creativity, but also, in a way, to the community as a whole; without the community's recognition and further development of Parisi's ideas, the impact would not have been as large. The Nobel Prize acknowledges that complex systems science has required original ideas, mathematical tools and computational approaches beyond (or that are orthogonal) to what is used in more traditional areas physics. The understanding of some computational, biological and complex networks problems that we have now, would not be possible without Parisi's contributions and of those who followed.

- **Robustness and fragility of complex systems**

In general I think that complex systems are often considered resilient and robust against systemic perturbations, but we know that sometimes 'small' events can have system-wide negative effects. If we take the brain as an example, we know that this is a complex system that can maintain its basic function even in adverse conditions. However, it is also fragile to certain system-wide and local perturbations: for instance, systemic imbalances in neuro-transmissor concentrations often result in behavioral or attitudinal disorders, and even mental diseases; other local perturbations, such aneurisms can result in irreversible damage to brain function. If we take ecosystems as an example, we know that while they are surprisingly adaptive and robust against adverse conditions, the arrival of invasive species, the changes in the habitat due to climate-change, and human activity in general can severely alter the equilibrium of an ecosystem.

In general, complex systems are often connected to many external factors. Fortunately, complex systems are typically adaptive and robust in response to 'small' changes in those external factors, but are fragile against large fluctuations other perturbations.

- **Prediction in/with complexity**

Long-term prediction is an issue in complex systems science. I think that there are different causes of our poor ability to predict: noise, the number of data points and lack of good models. Most of the time we do not look for generative models for our data, i.e. we use heuristics as opposed to using principled approaches that can quantify uncertainty rigorously given a few assumptions. When we do, noise or scarcity of data (or a combination of both) make it hard to make predictions. In fact, we know that there is a fundamental limit to our ability to recover models from data with noise [52, 53]. Because we typically cannot lower the level of noise, our best option is to increase the number of observations for us to be able to obtain predictive models for our data. Indeed, the development of tools to obtain mathematical models from data has revealed that typically there are many mathematical models that are compatible with observed data and that it is our role to increase the observations where it matters the most [52].

- **Advantages and challenges of interdisciplinary research**

For me one of the big challenges is communication. Researchers in other areas have a different language and sometimes lack the technical, quantitative training that scientists in the hard sciences have. As a result, we need to make a big time investment to be able to really cross the disciplinary boundary to build synergies. Some scientists perceive this as an unsurmountable barrier because it sets them back in their productivity path. Despite the communication challenge, in my mind the advantages of interdisciplinary research make the time investment worthwhile: scientists in different areas have a different outlook on specific research problems that is often complementary to yours and that enriches your critical thinking. By considering different angles of the same problem, interdisciplinary teams have the potential not only to significantly advance science, but also to make these advances known and acknowledges in different areas in science.

- **Final comments**

We should really take advantage of this opportunity to show the society in general the importance of complex science research at a practical level. I think that the contribution of complex systems scientists to the COVID-19 pandemic has already showcased how complex systems science can give answers to questions that are really close to society.

I also think that, for a long time, complex systems science has been seen as this 'lesser' discipline within physics. The Nobel Prize 2021 presents us with an opportunity for complex systems science to claim a long-awaited and fully-deserved spot next to the 'big' disciplines in physics.

16. Perspective of Maxi San Miguel

Maxi San Miguel

IFISC (CSIC-UIB), Spain

- **Defining complex systems**

Complexity comes the Latin word 'plexus' which indicates non-separability in components. Therefore, a good standard definition is that a complex system is composed of many interacting units showing emerging properties that can not be understood in terms of the properties of the individual isolated components. When we say that a system has emergent properties we mean that an effective theory of the system at some scale or level of organization is qualitatively different from the lower level scale. Quoting the Nobel Laureate Phil W

Anderson [54], a reductionist hypothesis does not by any means imply a constructionist one: one can then say that, as a change of scientific paradigm, complex systems science is the triumph of emergence over reductionism. Two important characteristics of complex systems behavior is that it is often associated with multiscale problems and that there are intrinsic limits for long time quantitative predictions.

- **Biggest challenges in the next twenty years**

I would distinguish three different aspects:

∗ At a basic scientific level there is still much to do in the development of general methodologies to deal with multiscale problems and to identify relevant variables for emergent behavior: what are the details that are important for global system behavior? Additionally, there is the challenge of the use and **understanding** of artificial intelligence techniques to establish cause-effect relations in complex systems behavior.

∗ As for specific challenging fields in which complexity science should have important impact, I would identify among others: (i) health sciences, (ii) collective phenomena associated with human-technology (including robots) interactions. More generally, complexity engineering, the engineering of complex systems for specific purposes, as for example nonconventional computing, is a challenging window of opportunities.

∗ As for social relevance, the biggest challenge is in terms of communication and education: (i) make society at large aware that the complex systems approach entails a scientific renaissance based in a different way of thinking with capabilities to transform society by transforming the way of thinking. (ii) Construct a new education system in which students of all ages learn the new way to learn about reality: learning across disciplines, learning from data.

- **Implications of the 2021 Nobel Prize**

It is a recognition of a mature field of research with fundamental contributions (spin glasses) as well as very socially relevant outputs (climate models). Climate is an emergent phenomena in the complex system 'Earth', and a particularly relevant example of a system with interaction at many different scales: from local variables to ocean-atmosphere coupling to planet level correlations. A main link between the two parts of the prize is the contributions to the concept of prediction. Quoting Giorgio Parisi [55], in the study of complex systems the word prediction has a weaker but more general sense, so that the target field of physics is much broader and physics constructions (concepts, models, tools…) have much more applications. Prediction in climate is now intrinsically probabilistic and based in realizations of different models ('replicas' of the climate system). The Nobel Prize is also a recognition of the interdisciplinary approach at the core of complex systems research as highlighted by the transfer of concepts form spin-glass theory to a variety of different problems.

- **Prediction in/with complexity**

Understanding, prediction and control are different things. Taking the Solar System as an example, we have a very good understanding of it, but we can not control it. On the other hand, the Ptolemaic Solar System based on data, was very good in predicting, but poor in scientific understanding. As discussed in my answer to previous questions, the concept of prediction is different in complex systems, being largely probabilistic or associated with forecasting of different scenarios. What we have learnt is that there are limits to what we can predict: we can not give a good quantitative prediction of the temperature in Times Square on July 4, 2031. The other lesson is that we have to identify which are the questions that can be answered. We need to understand better the limits of predictability (or the meaning of predictability) when dealing with complex systems.

- **Advantages and challenges of interdisciplinary research**

Interdisciplinarity, clearly different from multidisciplinarity, is the glory and misery of complex systems science. The glory is the transfer of concepts and methods among different disciplines, being this a great source of new knowledge. The misery is that when the general complex systems approach is applied to a specific subject of study, if successful, it becomes a new independent discipline. For example: city science.

17. Perspective of Stefan Thurner

Stefan Thurner[1,2,3]

[1]Medical University of Vienna, Austria
[2]Complexity Science Hub Vienna, Austria
[3]Santa Fe Institute, United States of America

- **Defining complex systems**

I believe a complex system must be co-evolving of some sort. The states of the elements change as some function of the interactions they have with each other, and the interactions change as some other function of the changed states. Interactions can be thought of temporal networks, or hypergraphs, or any higher order of network. In that sense complex systems are a natural extension of physics, where one is not limited to matter and to four types of interaction that (practically) never change. The physics of complex systems is the science of temporally changing forces (possible multiple ones of similar strength) due to particular and specific interactions. The essence of a science of complex systems is that the 'context' in which a system of interest evolves is also part of the co-evolving dynamics. This can be thought of as co-evolving multilayer networks. If a system is not co-evolving in that sense it remains in the realm traditional physics: finding solutions to equations of motion (or other update rules) under a few fixed forces and initial and boundary conditions—maybe complicated but nothing complex.

- **Biggest challenges in the next twenty years**

To convince the mainstream that the framework of complexity science can solve certain problems better and that it helps to map fundamental limits of understanding that arise from the challenge of understanding macroscopic 'causality' in complex systems.

- **Biggest challenges in the next twenty years**

Visibility and a well-deserved recognition in the early steps in the direction of an extended view of what physics will be able to become the coming decades.

- **Robustness and fragility of complex systems**

Complex systems are robust, but they also carry the grain of their collapse within them. One feature of complex systems that highlights the 'fragility' in complex systems is the nature of its underlying non-Gaussian statistics: power-laws. These imply that outliers are the norm rather than the exception—large and non-trivial fluctuations abound. The collapse of complex systems is often associated with massive restructuring events of the links in a networked dynamical system (interactions). If the system is resilient, the linking can be re-established in some sense, so that after a while the system functions as it did before—or perhaps differently.

- **Prediction in/with complexity**

This comes largely from the many degrees of freedom that have to be taken into account simultaneously. To make good predictions, one often has to rely on a good understanding of causal microscopic interactions, which can be incredibly many. The ever increasing availability of big data certainly helps. If interactions are also non-linear, things get even more challenging. Yet—and this is one fantastic thing about physics—there can be 'universality', meaning that details do not matter so much for predictions of some features of collective behavior. The challenge is then to know for a particular system if it shows such universality and, if it does, to which universality class it belongs.

- **Advantages and challenges of interdisciplinary research**

The advantage of sitting between fields is to have a chance of making bigger than incremental progress. Often in history, most progress made is at the boundaries of scientific fields, not in its core. The challenge is that in order to be truly interdisciplinary at least one collaborator should have a sufficient understanding of the involved fields. That needs extraordinary discipline. If this is not taken seriously there is the risk of being accused a mediocre scientist and not much progress is made. There exist embarrassing examples.

- **Final comments**

I am a deep admirer of the Laureates who pushed the understanding of complex systems in the way they did, and doing so in a crystal-clear way.

18. Perspective of Taha Yasseri

Taha *Yasseri*

University College Dublin, Ireland

- **Defining complex systems**

Instead of redefining complex systems, I would like to focus on two particular features of complex systems that are more related to our social lives today. The 'emergent behavior' and the 'unpredictability'.

The emergent behavior that is known to be one of the main features of a complex system is when the system's behavior cannot be explained and predicted by solely analyzing the behavior of its parts, in other words, the whole is more than the (linear) sum of the parts. Emergence is the core concept in understanding how our societies formed and changed over the course of evolution. At some point, we understood that the collective benefit of forming larger groups grows non-linearly with the group size and that became the driving force behind the formation of groups, tribes, villages, towns, cities and later countries and even bigger global social structures; so it is fair to say that the prominent example of emergent behavior is our social life.

Non-linearity is the mathematical manifestation of emergent behavior and is closely connected to another feature of complex systems that is unpredictable responses to perturbations. In the language of social sciences, this could be for example equivalent to unintended responses to policies and changes in policies. The cobra effect for instance is a very good example where a policy, through feedback loops and nonlinear responses, leads to unintended outcomes [56]. To reduce the population of venomous cobra snakes a 'bounty' scheme was initiated, and proved to be successful, however soon individuals started breading snakes to gain more reward. When the scheme was consequently terminated, there were, allegedly, more snakes! This is where, I believe, complexity science and the community of complex system scientists can provide invaluable insights into policy-making reminding and warning the policymakers of the unintended consequences of their actions. In summary, the most important features of social complex systems to me are emergent behavior and nonlinearity; both have significant implications in our social lives.

- **Biggest challenges in the next twenty years**

In terms of the research domain, I believe that the biggest challenge in the next twenty years in complexity science is to understand, predict, design, and control the interconnected socio-technical systems that we are living in today. Thanks to advances in Information and Communication Technologies, robotics, AI, G4 and soon G5, the complexity of the environment and agents that we interact with has increased dramatically. Our personal, social, and professional lives are now embedded in human-machine networks [57]. Our co-existence with semi-intelligent machines in these multilayer networks [29] naturally leads to unpredictable outcomes [58] some of which could be catastrophic such as pandemics or irreversible changes in the climate, while some could be beneficial such as Internet-based collective intelligence and crowd-sourcing initiatives [59] and citizen science projects [60]. It is important for the complexity science community to identify, study, and understand the features of these interconnected socio-technical environments.

In terms of methodology and epistemology of complex systems studies, we have passed those days when the main challenge was to find fine-grained empirical evidence for complex systems theories. The digital nature of our societies naturally leads to the generation of an unprecedented amount of transactional data, aka big data, that have been the main material in complex system studies over the past twenty years. However, the ever-existing problem of correlation vs causation has not been resolved by observational studies relying on big data. The next methodological challenge in the complex system studies, and particularly social complex behavior is how to design and conduct behavioral experiments that are ethical, scalable, and yet capable of pointing out causality and help validate existing theories and generate new ones fitting the new observations in the ever-changing socio-technical systems. This goes in line with the need to more rigorous statistical analysis beyond linear regressions and p-value analysis [61].

- **Implications of the 2021 Nobel Prize**

The recognition of complex system science through the Nobel Prize is an invaluable achievement for the community. For several years complex system studies, similar to any other interdisciplinary, or, for the lack of a better word, anti-disciplinary field of research, have been struggling to define their position in academia, gain access to funding and resources, and create meaningful relations to the industry and policy-making bodies. Nevertheless, with the ever-growing recognition amplified by this Nobel Prize, there is hope that some of these issues will be less challenging in the years to come. It is important now to note that in the public eyes, complex system science has gone far beyond phenomenological studies limited to observations of distributions or visualisation of networks only! Those initial empirical observations and insightful visualisations have been followed by deeper understanding of mechanistic models [62] and interpretations with real world implications [63]. Complex systems science is now solid science relying on scientific methods to tackle the most challenging issues in our societies.

- **Robustness and fragility of complex systems**

To me, the best manifestation of the paradox of robustness and fragility is self-organised criticality, where the system organises itself into the point of criticality where divergence and lack of scale appear. The system is robust in moving itself towards that point of divergence. In real-world terms and in the context of social sciences, the self-affine organisation of our societies is a robust behavior nevertheless the stability of social organisations such as social groups, companies, and cities, are not necessarily granted [64]. The very first mechanisms that are behind the birth and growth of social structures can lead to the decline and destruction of them. On its whole, the ecosystem of social organisations is stable around the point of criticality, where one finds divergence and scale-free structures across organisations making up that whole.

- **Prediction in/with complexity**

My answer to this question is related to the answer to the previous question that is unpredictability is a core feature of a complex system due to its very definition. Nevertheless in practical terms, there are numerous examples where mathematical modelling combined with accurate measurements, and advanced computational tools have improved our power of prediction to a significant amount. Today hurricanes and other climate disasters catch us by surprise to a much lesser extent than 20, 50, and 100 years ago. Even though the climate behavior has arguably become less predictable, nevertheless advancements in our understanding of climate systems, more accurate meteorologic measurements and the power of the availability of supercomputers that are being used to make weather forecasts, have enabled us to avoid catastrophic events to a much better extent.

Similarly, our socio-political behavior has become more 'turbulent' due to the widespread use of social media [65], however the digital footprint that we leave on such platforms combined with computational tools and complex systems approach to characterising the hidden patterns, can provide a great opportunity for policy makers to understand and respond to social needs of the citizens they represent [66].

- **Advantages and challenges of interdisciplinary research**

As mentioned earlier similar to any other interdisciplinary field of research complexity science has been struggling to gain the recognition that it deserves in academia and gain access to funding, secure jobs, and attract the best students who were less confident about the career opportunities following a path in complex systems studies. The main issue outside of academia has been the challenge of how to connect the findings of complexity science to real-world problems. Complexity sciences to some undesirable extent, have remained rather theoretical and or intellectual only. There is hope that the selection of complexity science for the Nobel Prize in 2021 help us overcome both of these problems.

- **Final comments**

It is in the spirit of the Nobel Prize that it should go to the research that has the most positive effect on human life [67]. Another aspect of the recognition of complexity science through the Nobel Prize is the responsibility of the community to make sure that complexity sciences go beyond the intellectual endeavors and to translate the findings and the generated insights into applicable guidelines and day to day knowledge that can be beneficial to the humankind at all levels from individual to global.

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