Understanding complexity paradigm and sustainability of complex systems: The role of theoretical physics

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Abstract. This brief review discusses the complexity paradigm and the sustainability of complex biological, ecological, and socio-economic systems. This paradigm is considered to complement the reductionism paradigm in explaining the natural phenomena. We suggest that the concepts used in theoretical physics can be considered to describe the specific case of complex systems and to develop their dynamical models.

Keywords: Complex systems, complexity paradigm, reductionism paradigm, sustainability, theoretical physics

1. Introduction

The root of modern sciences can be traced back to circa 10th century AD, namely when a scholar of the medieval Islamic era, Abū ’Alī al-Ḥasan ibn al-Ḥasan ibn al-Haytham, or Alhazen for short, introduced for the first-time the skepticism-based modern scientific method [1]. This systematic method allows one to study natural phenomena and put their descriptions into what we know today as scientific knowledge.

The scientific method was then elaborated further by some prominent western scholars such as Francis Bacon and René Descartes and led to the flourished of modern sciences in western civilization via the historical renaissance era [2]. One of the most significant contributions of the renaissance era to the development of modern sciences was the paradigm of reductionism introduced by Descartes. The paradigm has been historically proven to allow humankind to witness the birth of modern physics, chemistry, biology, etc, which is responsible for the advent of modern technology.

The reductionism paradigm, also known as Newtonian paradigm, can be briefly explained as an attempt to understand natural phenomena by reducing an observed system into its sub-systems, and studying them separately, assuming that there are ignorable-interactions among the sub-systems. The paradigm assumed that knowing all the sub-systems' characteristics will lead to understanding the system's characteristics as a whole. Physics, including theoretical physics, which has been considered one of the most ultimate scientific disciplines that shaped modern civilization nowadays, heavily relied on this paradigm over the past 300 years, namely, after Isaac Newton laid its foundation [3].

However, the corresponding reductionism paradigm has been subject to question due to its inability to understand the system's properties as a whole. This paradigm has failed to understand the emergence of a specific property of the whole system, which cannot be explained simply by looking at the sub-systems' properties. Life system, ecological system, and social system are among systems that cannot
be comprehensively described within the reductionism paradigm, especially on the issues related to their sustainability.

In this paper, we briefly review a different paradigm, i.e. complexity paradigm, which is recently considered to complementing the reductionism paradigm in describing a system as a whole due to the existence of emergent property such as sustainability. We also discuss the role of theoretical physics to provide the analytical concept for this new paradigm.

2. Complexity Paradigm and Sustainability of Complex Systems

Based on current understanding regarding how the universe works, at least it described by three fundamental rules, namely (i) its dynamical stability obeys the principle of minimum energy, (ii) controlled by simple rules, and (iii) exhibit symmetries. Along with those fundamental rules, scientists have identified that our universe is build-up by a simple matter-energy structure consisting of 70% dark-energy, 26% dark-matter, which are unknown up to now, and 4% ordinary matter-energy, which is fundamentally consists of leptons and quarks [4]. All these matter-energy forms are interacting through four fundamental interactions: strong nuclear force, weak nuclear force, electromagnetic force, and gravitational force [5], where in our mesoscopic perspective, all of those interactions exhibit either repulsive or attractive property.

All things in the universe can be principally decomposed into a system and its surrounding environment, which is separated by a specific boundary. A system consists of a collection of sub-systems. In the reductionist paradigm, which is also known as Newtonian paradigm, where the universe dynamics is assumed predictable, one can deductively know all the system's properties by merely considering all sub-systems' properties and assuming that the interactions among the corresponding sub-systems are weak, which can be treated perturbatively. In other words, this paradigm considers the principle of superposition to describe the general properties of a system. Despite this paradigm's success in describing the particular dynamics of natural systems, there are many other properties of the so-called complex systems that cannot be deduced simply by characterizing their subsystems' properties.

Similar to the other systems, a complex system also consists of sub-systems. Nevertheless, nonlinear interactions occur among those sub-systems resulting a new property which is different that the property of all sub-systems. A complex system can be at least characterized by (i) the attributes of each sub-systems, (ii) the network of nonlinear interactions among its sub-systems, and (iii) the rules that guide those interactions [6].

Let us take for an illustration water molecule as a complex system. Water molecule H₂O consists of two different atoms namely hydrogen (H) and oxygen (O). In-room temperature the water has a liquid state. In contrast, its sub-systems, namely H and O atoms with all their individual attributes such as mass, charge, angular and spin momentums, have a different behavior, where at room temperature they constitute H₂ molecule, which is flammable and in a gas state, while O₂ molecule is known to support fire and also in a gas state. Under the reaction 2H₂ + O₂ → 2H₂O, a nonlinear interaction occurs between H and O in such a way through the covalent bond, and between H₂O molecules through the hydrogen bond, such that the water has a totally different state and behavior. Note that in its relation with fire, water has an ability to be a fire extinguisher.

The liquid state of H₂O, which is different from the gas state of H₂ and O₂ molecules at room temperature, is called “emergent property.” Its sub-systems do not own this property as an isolated system. Although this phenomenon still not clear up to now, the occurrence of this new emerging property is likely due to the existence of nonlinear interaction among those substituent atoms that induce the process of self-organization.

In general, the existence of emergent properties is the primary feature of a complex system. Based on this example, it is readily seen that the perspective of reductionism cannot be applied to demonstrate and describe the occurrence of emergent properties in general. So, it is likely needed to consider a new paradigm, namely what we called “complexity paradigm.” This paradigm can be explained briefly as a new perspective to consider a system as a whole nit by reducing it into its sub-systems. One of the best
statements to describe this new paradigm is by saying that “the whole is greater than the sum of its parts” [7].

Indeed, there are a lot of complex systems that exist in our universe. The hadron particles, e.g., proton and neutron, consisting of three different types of fundamental particles called quarks, can be considered as a complex system, exhibiting emergent property. Its emergent property is likely due to the strong nuclear interaction. Likewise, the atoms that consist of hadrons in the nucleus and a class of fundamental particles of lepton known as electron, also constitute a new level of complex systems with a new type of emergent property through the electromagnetic interaction. Going up to a larger scale, we can find a different complexity level with certainly exhibiting other emergent properties.

The biological, ecological, and human-socio-economic systems are among systems with a higher complexity level and a vast number of known emergent properties. The human body, forest ecosystem, and global market are good examples for each system, respectively. All those systems are nothing but primary systems that build-up our earth system in general. In this context, it is clearly understood that understanding the dynamical behavior of those systems cannot be conducted based on the Newtonian paradigm. Studying them through this paradigm will omit the possibility of adequately understanding the nature of its emergent property.

It should be realized that one of the most critical issues related to those biological, ecological, and socio-economic systems are their sustainability issue, which is very important to provide certainty for our future generation [8]. In terms of complexity paradigm, a complex system's sustainability can be defined as an emergent property where the system is always to be in its dynamical equilibrium with ignorable disadvantage dissipation. Characterizing its attributes and understanding the related nonlinear interactions within a complex system by mapping out its network among sub-systems is likely playing a significant contribution in maintaining the corresponding sustainability condition. In the next section, we discuss that, to some extent, attempt to explain the dynamics of a complex can be conducted utilizing approaches that are commonly used within theoretical physics.

3. The Role of Theoretical Physics

As mentioned above, for a complex system that consists of many nonlinearly interacting sub-systems, merely applying the superposition of each sub-system cannot predict the occurrence of its emergent property. Based on this, the complexity paradigm offers a new holistic perspective to the system as a whole, without studying sub-system as an individual system and considering the interaction with other sub-systems non-perturbatively.

From physics point of view, complex biological, ecological, and socio-economic systems can be considered similar to the other physical systems that have been traditionally studied. For example, a gas system, which is nothing but a mere collection of interacting molecules, has been a physical object that physics traditionally studied intensively.

It is well known that by assuming that each molecule of a gas system: (i) each molecule is considered as a point-like particle, (ii) each molecule has no direct interaction with other molecules through mechanical collision, (iii) only interact with the boundary wall via elastic collision, (iv) the only physical attributes included in the theoretical formulation are their mass and velocity. Based on the statistical physics approach one can develop theoretically the equation of state of such gas in the form of the celebrate ideal gas equation: \( PV = nRT \) [9], where P is the gas pressure, V and T denote the gas volume and temperature, respectively, while n and R are the mole fraction of gas and the universal gas constant, respectively. Indeed, a different assumption will lead to a more complicated equation.

Note that in terms of complexity paradigm, the P and T parameters are nothing but emergent properties of a gas. It is the properties of the gas as a whole and not the property of each individual molecule. In this exemplified case, the statistical physics as a branch of theoretical physics that deals with rationalization, explanation, and prediction of phenomena in natural systems developed based on the combination of mathematics, abstraction, imagination, and intuition, has been proven powerful to describe such system.
From this illustration, one can imagine that, for instance, a traffic system as a part of large human-socio-economic systems can be treated similarly to a gas flow system under different assumption. The concept of entropy can be used to describe its dynamics and to learn its self-organization process [10]. The case of opinion spreading among people in a social community can also be discussed using the concept of entropy to show the possible opinion phase transition due to the existence of a stubborn person [11]. Another interesting example is the consideration of using quantum theory description to model the interaction between the brain’s amygdala and prefrontal-cortex to explain the decision-making process in a two-player game [12].

It should be noted that not only statistical physics and quantum theory description that can be used to model the aforementioned complex systems. Other approaches traditionally used in theoretical physics, such as the dynamical system [13] and fluid dynamics [14] formulation, can also be considered. Recently, due to rapid development in computer technology, one can also consider the discrete agent-based model for specific complex systems [15]. This approach's implementation is similar to what has been conducted in modelling a physical system, namely by considering each sub-system's attributes, defining the network of interactions among them, and utilizing physics concepts. All these attempts are likely important to maintain the complex biological, ecological, and human-socio-economic systems to be always in their dynamical equilibrium emerging the sustainability condition.

4. **Summary**

We have discussed in this review paper the new paradigm of complexity. We show that this paradigm complements the reductionism (Newtonian) paradigm, especially when dealing with complex systems. One of the most important features of a complex system that consists of many nonlinearly interacting sub-systems is the appearance of emergent property, which is not found in each sub-system. One of the most important issues in complex systems is their emergent property of sustainability related to a dynamical equilibrium with ignorable dissipation. Theoretical physics, which is developed based on the combination of mathematics, abstraction, imagination, and intuition, has been proven to describe complex systems' specific case by using several approaches, e.g. statistical physics, quantum theory, and dynamical system and fluid dynamics.

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32

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