Emergence in general science

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Emergence is an omnipresent phenomenon that is present in almost all subjects, including physics, other branches of natural science, languages, and even social sciences and economics. Similarities and differences can be found in these domains. We discuss the classification of emergence, which can be organized according to different rules. We also explore universal properties among different levels of emergence, and where the differences among emergence patterns in different theories come from.

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I. INTRODUCTION

Emergence is the phenomenon that a macroscopic phenomenon/system is not fundamental but instead an approximation from coarse-graining of underlying microscopic degrees of freedom. The term ”emergence” has a long history in metaphysics [1], proposed as a kind of cumulative change which leads to a new level of characteristics. As our understanding of emergence evolves with the rapidly expanding discoveries and researches, emergence has found its role in almost all subjects, including the natural sciences as well as the social sciences. Initially, emergence was used to describe the different phases in physics, where gas, fluid, and solid all emerge from microscopic discrete molecules. The original definition of emergence is well represented in this example, where it is impossible to see that the building blocks are tiny molecules from the macroscopic scale, and vice versa. The concept later found its presence in biology[2–4], chemistry[5–7], social sciences [8–10], economics [11–13], etc. These phenomena of emergence include many different levels in the same context and various intersections among diverse subjects. Our understanding thus becomes highly enriched and deepened thanks to the various scenarios which provide abundant properties of emergence for us to study. However, to understand emergence clearer and deeper in view of all these complicated phenomena, efforts should be made concerning the clarification of emergence, the relationship between different emergence, the common structure and specialties of emergence, and the ways to describing emergence in a unified way.

In this paper, we discuss several essential issues concerning emergence in general. Firstly, we introduce and review the emergence phenomena in a wide variety of areas in sec II. We then discuss several classifications of emergence from different perspectives in sec III. Sec IV serves as a conclusion of this paper.

II. EMERGENCE PHENOMENA

To study emergence in general science, we first introduce and review emergence phenomena in a wide range of areas. This includes emergence in physics, chemistry, biology, neural networks, social science, and economics.

A. Emergence in physics

The most extensively studied area of emergence is of course physics, as it includes the studies from the smallest scale of spacetime all the way up to the largest scale in the universe, and from the beginning to the end of time, if any. In such a wide range, emergence occurs at many different levels. Fundamentally, the building block of our universe, spacetime, is conjectured to be emergent from more fundamental entities [14–16]. Although whether spacetime is fundamental or emergent is still an open question not settled down yet, there have been a large quantity of studies on this issue both on the theoretical realization and philosophical implication. By AdS/CFT correspondence, the rule of how gravitational spacetime emergence from its holographic dual CFT are explored [14, 17, 18], where exact correspondence between the boundary CFT and the bulk AdS enables the reconstruction of the bulk spacetime from the boundary theory. This induced the ”It from qubit” program where spacetime is thought to come from information-theoretic origin. Different from the holographic scenario, entropic gravity [19] put it straightforwardly that spacetime and gravity emerge from the entanglement structure of the underlying microscopic theory. Apart from string theory and entropic gravity, all other quantum gravity theories contain descriptions of spacetime emergence [16], including loop quantum gravity, causal set theory, tensorial group field theories, causal dynamical triangulations, tensor models, quantum Regge calculus [20]. The emergence of spacetime in these quantum gravitational theories, though leading to the same outcome, i.e., spacetime from the underlying microscopic structure, are different in the philosophical sense. After spacetime emerged, other fundamental entities emerge on this basis. The creation and annihilation of fundamental particles are a kind of emergence. After fundamental particles emerge out of vacuum, they serve as building blocks for further emergence. This emergence from fundamental particles appears in varied forms. The collection of fundamental particles, formed essentially by quantum particles, can give birth to a classical many-body system as well as quantum many-body system, due to the parameter regime that the system is in. Macroscopic laws that are absent in microscopic physics emerge as the macroscopic structures emerge. Thermodynamics, with time arrow emerging from time-reversible microscopic physics. The emergence of a system from a large number of fundamental particles can also fall into different categories by whether the system is ordered or disordered.

Solid system, liquid system, gas system, plasma system, Bose-Einstein condensates, Fermion condensates, neutron-degenerate matter and quark-gluon plasma all emerge from fundamental particles. The story does not end here. Large quantities of the matter emerging from fundamental particles give rise to the formation of large scale structures, varying from a rock, a mountain, a river, an atmosphere to a planet, a galaxy, and the whole universe. Emergence in physics thus covers a very large scale with abundant patterns.

B. Emergence in chemistry

Let us turn our gaze towards emergence in chemistry. Emergence in chemistry deals with a range smaller than that in physics, corresponding to the smaller domain of chemistry itself. The smallest level comes down to a single atom, and the largest scale goes up to the chemical composition of the universe. It is quite limited in comparison to that of physics, due to the fact that chemical interactions, therefore, the chemical bonds, are the inter-atom or inter-molecule forces. However, the phenomena of emergence are abundant as well because of the large variety of chemical properties. Not all chemical properties have clear demarcation with that of physics, and in some sense many chemical properties emerge accompanying the emergence of physical structures. It is believed that if the question of emergence is separated from that of physics, there would be no complete description left. The reduction of the emergence of chemistry to quantum mechanics has always been a question in the philosophy of chemistry[5, 21]. The debate on this reduction shows the essential problem of whether the reductionism of chemistry to fundamental physics is possible. This question is deeply rooted in our lack of ability to deal with many-body systems. The exact solution of a three-body interacting system is already beyond the reach of analytic theory. And chemical interactions whose exact physical description requires solving the Schrodinger equation for atoms and molecules, are far beyond our reach as any atom apart from the hydrogen atom is not exactly solvable. Therefore, despite our knowledge of the fundamental laws of physics, the emergence of phenomena cannot be straightforwardly derived without introducing approximation methods to deal with the process of emergence; empirical rules are often employed to describe chemical laws. Typical emergence phenomena in chemistry are: the emergence of molecule structure and therefore the periodical table; macroscopic properties like temperature, density, color, flavor; structural properties of crystals; phase transitions; chemical balance; even chemical interactions are emergent phenomena which require due temperature, pressure, and density that are absent in a single molecule. Many effective theories are employed for chemistry instead of deriving the chemical properties and chemical transformations from quantum mechanics from scratch. The complicated patterns of chemical reaction indicates that the reductionist's view, that sciences are hierarchically ordered and unified are not applicable for all scenarios.

C. Emergence in biology

Closely related to emergence in chemistry is the emergence in biology[3, 22, 23]. The regime of biology is even smaller than that of chemistry, ranging from ions, molecules to the biosphere. The patterns of biology, however, are much more complicated than those of physics and chemistry. The emergence of phenomena in biology involves a large variety of interacting scales, and complicated interactions among different individuals as well as species. Here we introduce the emergence in biology according to the scales involved. The smallest scale in biology contains ions and molecules, where organic and inorganic molecules are included. Through combination of organic molecules, components of cells emerge, while specific combinations of organic and inorganic molecules and ions lead to the emergence of cell sap. Cells emerge from these components. Based on cells, tissues emerge. This emergence is relatively simple as tissues are constructed from regular combinations of the same type of cells. Organs further emergence from the combination of tissues. Systems emerge from combination of organs, where system and organs are usually of the same scale. Individual creatures then emerge from systems. A collection of individual creatures lead to the emergence of population, and ecosystem emerge from the collection of populations. Finally, all ecosystems come together to form the biosphere. The hierarchy structure in the emergence in biology is therefore very clear, while on each level, the phenomena are rich, resulting in the diversity of lives[24].

D. Emergence in deep learning neural networks

Emergence in deep learning neural networks is less complicated and easier to describe[25? –27]. Although the inspiration for neural networks comes from neural networks in human nervous system, where perceptrons bridge the gap between different layers, it is essentially a kind of data processing procedure and does not involve complicated interactions of different kinds of entities. The most common meaning of ”emergence” in neural machine learning is the appearance of abilities for which the model has not explicitly been trained. The variety of emergence in deep learning neural networks due to its application to an enormous range, such as image processing[28] and identification, music composition [29], data processing[30], simulating experiments[31], analyzing structures[32], and disease diagnosis[33] etc. Emergence of deep learning neural networks therefore is basically characterized by its function, i.e., what problem it can deal with. In realizing the function, various neural networks were developed. In some sense, it is not as complicated as the emergence of physics, due to its much smaller range; and not as complicated as the emergence in neural network, as it just handles data but does not have any emergent consciousness.

E. Emergence in language

The emergence of languages is a basis for human studies [34], where linguistic forms emerge from self-organizing systems. There are a large variety of languages that serves as example for the study of emergence. Basically, in any language, there is a set of basis components, be it letters or characters. These letters or characters, if arranged randomly, does not lead to language. The rules for organizing these basis components are essential and lead to the emergence of languages. The levels of emergence of languages are similar. Firstly, the letters or characters are organized into words, which sometimes already represent some meanings. However, prepositions and auxiliary words usually do not have meanings independently. Secondly, sentences emerge from the regulated combination of words and phrases, this procedure follows many rules that determine the emergence of sentences. Sentence further organized into paragraph, where there are still rule regulating the formation of paragraphs, as correct sentences combine together without a gist would be nonsense, as is the emergence of an article from paragraphs and a book from chapters. The emergence of languages combine the laws of social sciences and physics: it originates from the evolution of society [35], is aimed for social usage, and then plays important role in social activities and the evolution of societies. On the other hand, the emergence of language follows the laws of statistical physics [36], and manifests the features of self-organizing systems. In the literature on emergence of language, there have been many specific focuses [34], i.e., the emergence of auditory patterns, the emergence of articulatory patterns, the emergence of the first words, the emergence of inflectional marking, and the emergence of syntactic patterns(which includes the emergence of parts of speech and the emergence of argument structures). There are different frameworks dealing with the emergence of language. The emergentist framework emphasizes ways in which the formal structures of language emerge from the interaction of social patterns, patterns implicit in the input, and pressures arising from general aspects of the cognitive system. On the other hand, In the self-organizing framework, the learning of a word is viewed as the emergence of an association between a pattern on the auditory map and a pattern on the concept map through Hebbian learning. The emergence of language, as it is inseparable from human action, is not an autonomous process which is completed with unconscious participants, but a result of competition. Language acquisition is believed to emerge from the competition between alternative competing expressions.

F. Emergence in social sciences

In social sciences, the basic elements are individuals. Hierarchy structures emerge from the collection of human beings. The emergent phenomena in social sciences are the collective actions of human beings, which in different activities show different hierarchy structures[9, 37]. Take politics as an example. The simplest emergent phenomena should be the emergence of social organizations, politically, human individuals organize level by level, from a individual, all the way through family, district, township, county, city, state, country all the way up to a world. Upon this chain of emergence, many different functions can be associated. However, in other social problems, there could be different lines along which the emergence appears. For example, religion has it own organization which is not completely independent of the political organization, but has huge differences.

For any specific social activities, the organization and therefore the emergence of the resulting structure should have its own organizing rule. In modern society, political organization and economic organization exert strong interactions toward each other, and both have huge influence on social organizations around other motifs. In ancient times, however, religious organization have very strong influence upon the emergence of other organizations, and the formation and influence of the organizations are heavily dependent upon the ability of human beings to influence and control. If we focus on a single element of social science, we can find the emergence pattern from it as well [38], but this kind of emergence is not complete in the sense that it is influenced by other essential factors. The emergence in social sciences is not only built upon material entities like human individuals and the environment and products of human society, but also on intangible components such as knowledge, rules, concepts, and ethics.

G. Emergence in economics

In economics, emergence was not recognized by classical or neoclassical economics. But researchers then realized that without emergence, many phenomena can not be explained. Four schools of economics, i.e., the evolutionary, complexity, Austrian and spatial approaches developed different views and methods to analyzing the problem of emergence. Evolutionary economics employs emergence to explain long-run economic development and shorter-run transformation processes. For complexity economists, "emergent" denotes "stable macroscopic patterns arising from the local interaction of agents", where agents are computational objects that interact according to explicit rules encoded in a computer program. Emergence is thus a feature of a process generated by algorithms. Austrian economists use emergence concepts to explain how invisible-hand phenomena come into existence. In the view of spatial economics, emergence is seen as the product of nonlinear interactions of system components which is manifested in complementarities, external economies and positive feedbacks in regional development. The emergence in economics is generally a complicated phenomenon although many problems therein follow statistical rules[11, 39]. Usually, the term emergence of economical organization and concepts are different from what we are concerned here. In most contexts, it refers to the way these entities come into being. The emergence in economics we study here is instead the emergence of macro-scale economical organizations or actions that come from the collection of microscale economic entities. The basic component is not human individual alone, but also the resources, productivity, and many other factors that are indispensable in economic activities. Some of these additional factors can be treated combined with the human individual as a whole, such as productivity per person, and some should be treated as interactions that regulate the process of emergence. Beside the emergence related to human individuals, many problems in economics can be viewed from the particular abstract notions, such as behaviors, goods, technologies, firms, and markets etc. The studies on emergence in economics is not as objective as that in physics and other natural sciences. Conscientious has not been reached among different school of economics, and their interpretations of emergence differ.

III. CLASSIFICATION OF EMERGENCE

Having introduced the phenomena of emergence in several branches, we put them together and explore the common features as well as the differences among different patterns of emergence. In all branches of emergence, the most essential common feature of emergence is "much coming from little", manifested as complex, macro-scale structures generated from simple rules and microscopic components. The process of emergence itself, however, can have different properties.

A. Strong and weak emergence

The classification of emergence patterns into strong and weak emergence is common to studying emergence in all branches of science[40]. This is a conceptual definition which is not directly associated with mathematical formalism, and different people may view the same problem differently due to their conceptual difference. Strong emergence describes when the high-level phenomenon arises from the low-level domain, but truths concerning that phenomenon are not deducible even in principle from truths in the low-level domain, which implies that each level of a hierarchy of sciences has its own special laws. On the contrary, in weak emergence, the high-level phenomenon arises from the low-level domain, but truths concerning that phenomenon are unexpected given the principles governing the low-level domain. The concept of strong emergence has a much longer history than weak emergence, which is thought to play important roles in many daily concepts, i.e., life, mind, culture, chemistry, molecular structure, pandemics, global phenomena like superconductivity etc. The commonly accepted examples of weak emergence, however, only exist in simple systems like connectionist networks, flocking birds, traffic jams.

Although the definition of strong emergence and weak emergence seems to be clear-cut at first sight, when we examine the examples deeply, it's easy to realize that this classification is not independent of assumptions and our knowledge and understanding of the phenomena. Basically, to define a phenomenon to be weak emergent, we implicitly assumed that all other components works as the local component that we are given, that in the global system there are no other laws intervening, and that no other components comes into action. These are the assumptions from the local viewpoint of the global system. Without these assumptions, even the simplest emergent phenomenon can not be characterized as weak emergence. However, when it comes to more complicated systems, a question emerges: what kind of assumptions can we have on the global system from the local viewpoint? Take the example of life. Usually it is considered to be a strong emergence, as the laws of the whole body cannot be perceived at all. However, if our assumptions from the local system, say a single cell, include the information encoded in DNA, and the rule how DNA guides the emergence of the body, the situation becomes different. That is to say, if we have all the knowledge how DNA encodes the body construction process, then from the cell we could perceive the emergence of the whole body, whether it is strong emergence or weak emergence then depends heavily on the definition we choose. If we restrict the condition of weak emergence to be, we use the explicit local laws and behaviors, rather than hidden laws, another question emerges: before the discovery of DNA, we don't know at all how biological information is encoded in a single cell, but after we had thorough research on DNA's function, we do have that knowledge. There are vast differences between the previous and present situations, and the two situations therefore cannot be classified as the same. And suppose some day we finally got thorough understanding on coevolution, it may even become possible for us to predict the other species and environment around a given biological species. With these in mind, either we accept that strong and weak emergence is just a description of our current knowledge and understanding of an emergent phenomena, or we choose to classify a large variety of emergent phenomena to be "intermediate emergent", that is, we don't know whether it is weak or strong emergent due to the limitation of our knowledge. The demarcation between strong and weak emergence therefore more likely to be describing emergence from hidden laws and emergence from manifest laws (at our current knowledge), respectively. Therefore finally we have to admit that the classification of strong emergence and weak emergence relies heavily on our knowledge and understanding of the emergent phenomena, which may evolve with time. Practically, it reflects our current treatment of the problem, weak emergence can be treated with exact model (in principle), whereas strong emergence can only be treated with phenomenological model. This well accords with the common approaches to scientific problem: usually, a phenomenological model is proposed firstly to fit and explain the data, and employed to make predictions; but people are not satisfied, they then search for a model of first principle. In terms of emergence, the trends is to firstly accept a model of strong emergence, and then in search of a model of weak emergence.

B. Classification by order

Previously, there had been a classification of emergence according to the intrinsic order of the process[41], where there are three orders of emergence, which are distinguished from one another by the way recurrent causal architectures can be embedded in one another across levels of scales. The embedded relationships are non-recurrent, simple recurrent and hyper-recurrent causal architectures, leading to the classification of first-order, second-order and third-order emergence respectively. First-order emergence, as is classified, is commonly seen in physics, with the typical example as liquid properties, including laminar flow, surface tension, viscosity etc. Self-organizing properties are classified as second-order emergence, called morphodynamics. And third-order emergence, called teleodynamics, is characterized by an additional loop of recursive causality that transcends and encloses the second-order recursive causality of self-organized systems, which endows it with developmental and evolutionary character. This classification, essentially assigns different emergence categories by the types of interaction between the micro-scale and the macro-scale.

The classification in [41] mainly characterizes emergence corresponding to different domains. However, if the classification by order is completely formulated in mathematical terms, it would be easy to see that emergence phenomena in every branches may more or less fall into different orders. For example, in thermodynamics that is assigned to be first-order emergence, there are non-Markovian processes that manifest properties of third order emergence. In real life, first order emergence is just an approximation around a static point at a given interval where higher order emergence are of negligible magnitude. When the system considered evolves in time and space, essentially higher-order effects will become manifest sooner or later.

It should be noted that this classification is not practical in every problem of emergence. A pertinent classification should capture essential features which help understand the problem better or lead to immediate method to dealing with the problem. However, classification by order is too rough to give rise to models for emergence.

C. Classification by level

On the other hand, in studying the emergence of spacetime, in the functionalist approach, emergence is characterized by its level[16, 42]. This classification is quite different from the previous one, as it describes different emergence schemes for one emergent phenomenon, which usually corresponds to the progress of our understanding towards an emergent phenomenon. There is no universal definition on the levels of emergence for difference problems. For a certain problem, however, the definition of levels of emergence is subject to subjective judgment. For example, in emergence of spacetime, not only no consensus is reached upon the definitions of detailed levels, but the number of levels are subjected to different perspectives. Originally, [42] proposed four levels for spacetime emergence, where the primary level, i.e., level 0 corresponds to the earliest attempt at quantum gravity, that is the quantization of general relativity. Progressively, the subsequent levels of spacetime emergence show the deepening of our understanding. In the subsequent paper on level of spacetime emergence [16], however, the number of levels becomes 5. There is an additional level-1, which represents the concept that space and time get identified as relations among dynamical fields, including the metric field. Besides, in this paper the definitions on the other 4 levels are somewhat altered. The difference between the definitions in the two papers shows that to make the levels of emergence well-defined for a certain problem, the first thing is to distinguish between knowledge and assumptions, sometimes assumptions are so well-accepted that they are taken as knowledge. Whereas assumptions are assumptions, it may change when we discovered facts that disprove those assumptions. The definition of levels then not only rely our understanding of the whole problem, i.e., the emergence of spacetime as a whole, but also on what levels give best description on a phased understanding toward the problem, i.e., for a researcher working in 20th century, he could also classify the emergence of spacetime in 4 levels, however, that would be included in one or two levels of our current understanding. And when sometimes there is not phased consensus or discovery reached, there may not be good representation of a level.

Though proposed for studying the emergence of spacetime, this classification is not limited to emergence of spacetime, but is general to all kinds of emergence. It represent our understanding towards an emergent phenomenon that evolves with time. However, there is almost no common structure for the levels of emergence in different phenomena. Particularly, it hard to find a universal quantification of the levels. Basically, two levels must be common to all emergence. One is the lowest level: a kind of ”semiclassical” theory that starts from the known fundamental components to construct the ambiguous emergent phenomena using known theories. The other is the highest level, where the emergence of the phenomena finally becomes clear, and this level is subjected to our current understanding which provides a cutoff for the understanding of the phenomenon, unless the problem is completely solved. In real history of science, sometimes wrong levels emerge and become dominant for a while, until it is finally replaced by a correct new level. For example, geocentric theory is a wrong level, it may still be a level in history of science, but is no longer a level of the emergence of universe. Lamarch’ theory for evolution was a level of emergence of species, but no longer a level in our present understanding.

D. Emergence in open systems and emergence in closed systems

Emergence phenomena are hugely different in an open system or in a closed system, where an open system always exchanges energy and information with the external environment, and in some sense shaped by the external experiment. Therefore we propose classifying emergence according to whether it happens in an open system or a closed one. Example of emergence in closed system are rather limited, but limit the problem to a small time scope, or discuss the problem assuming a fixed boundary, we can have approximate closed system problems. For example, in discussing the emergence of liquid, gas or plasma from fundamental atoms and molecules, the whole system is usually assumed to be unbounded, as the boundary does affect the basis components. In discussing the emergence of a galaxy, the simplified problem does not take into account the exchange of matter and energy with the outer universe as those processes are of negligible small magnitude. However, emergence in open systems are more prevalent. The emergence of a sandpile or a snowdrift requires continuous input from the external system, and emergence of life depends on the feeding of materials from the environment, i.e., energy from sun and matter from the earth. In the problem of emergence of language, though the focus is upon language itself, as are the laws, the influence of language on human being and the feedback is indispensable for the emergence of language. And the emergence of economic entities and social pattern are often strongly influenced by world wide exchange. If we formulate this classification into mathematical forms, it would be easy to see that for emergence in a closed system, if the theory for the problem is clear, in principle we can describe and predict the emergence completely from the data of the system. However, for emergence in an open system, a theory cannot be derived within the system. The interaction with the external system may be handled with phenomenological parameters or terms, but no account can be given to these parameters from the system alone. Usually, emergent phenomena in open system may be a sub-emergence of a emergent phenomena in a closed system, and vice versa.

E. Continuous emergence and discrete emergence

In many scientific domains, there are continuous phenomena and discrete phenomena, where continuity is usually an approximation though which the description of the problem become integrable. In the problem of emergence, we can also classify the phenomena into two categories, i.e., continuous or discrete. Continuous emergence is a good approximation for many problems. Usually, it require that there is a large scale separation between the fundamental component and the final scale of emergence, for example, the emergence of phases in physics, where the scale separation is usually characterized by Avogadro constant. Due to the continuity of the problem, it can well be described by mathematical equations, a prevalent example is the emergence described by renormalization group flow [43], all those emergent phenomena that follows renormalization group flow can safely be seen as continuous emergence, which includes a large variety of phenomena in many sciences. Whether there are other continuous emergent phenomena that cannot be described by renormalization group flow remains to be seen. There are also abundant emergent phenomena that are discrete. For example, the emergence of an organ in organism is from several different tissues, but usually the magnitudes of the tissue and the organ are of the same order, the emergence is therefore discrete. The situation is similar when several organs form a system. In a stellar galaxy, usually the number of the stellar is only one, and the number of planets are limited, the emergence of the galaxy is therefore discrete. Discrete emergence inevitably leads to the failure of a statistical description, but has to be discussed with deterministic laws. Besides what have been discussed, there is another essential difference concerning reducibility. For continuous emergence, a statistical description is available, which indicates that in describing the emergent phenomena, many data have been thrown away, which is the origin why many emergent phenomena are not reducible. This can also been seen from universality depicted in renormalization group theory. Many different micro-theories flow to the same macroscopic fixed point, there is thus no one-to-one correspondence between a macro-theory and its underlying micro-theory. Owing to this fact, the inverse renormalization group, i.e., the reconstruction of the microscopic theory from the macro-theory, has to employ the microscopic Hamiltonian[44]. On the other hand, for discrete emergence, the component can be seen visibly, and reduction to components are more straight-forward.

F. Autonomous emergence and non-autonomous emergence

Autonomy is an essential point that sets the demarcation between the mechanical world and the living world. For emergence in physics and chemistry, the components, the laws and the results are purely mechanical. Nothing but the natural laws determine the process. When it comes to biology, economics, and social sciences, however, things are different. In biology, emergence is not mechanical pile-up of materials, but is organized according to designed purposes written in DNA. In social sciences, economics, language and deep learning neural networks, although the result of emergence may be described using mathematical models, there is an essential difference where the terms come from and how the rules are reinforced. The fact that in these domains self-conscious and self-decision count leads to a result, i.e., the models for emergence can only be a fit of the problem, or a statistical description, but can never characterize the origin of the terms therein. In this way, we can classify emergent phenomena into conscious emergence, unconscious emergence, and half-conscious emergence. Unconscious emergence includes all kinds of mechanical emergent phenomena with no autonomy. Conscious emergence, includes the phenomena where all actions are consciously done by organisms, human activities in social sciences and economics fall into this category, and the clustering and migration of animals are typical examples as well. Half-conscious emergence refers to emergent phenomena usually on sub-organism scale, where the emergence is not solely determined by mechanical laws, but also determined by biological laws, however, the organism itself cannot exert free will on those processes. The emerge of tissues, organs, and the periodical activities of viscus fall in this regime. It should be noted that mathematically, as long as the emergence is continuous, no matter autonomous or not, the process can be described by statistical models. Over a large scale, the influence of self-consciousness may appear as a source of fluctuations.

IV. CONCLUSION

In this paper, we put together emergence in several branches and analyze the properties of them together, i.e., physics, chemistry, biology, deep learning neural networks, languages, social sciences, economics. By looking into the properties of emergence in different domains, we summarized their universality and differences. The classification of emergence enables us to do the comparison and extract the essential features of emergence. We found that the classifications by order, level, open or closed, continuous or discrete are common to all branches of science, where the classification by level represents our current understanding of the problems, and the other classifications are usually manifest from the mathematical formulation. Whether the emergence phenomenon is autonomous or not sets the demarcation between mechanical emergence and emergence with consciousness. Owing to this difference, models for autonomous and half-autonomous emergence can not be derived from first-principles even in principle.

There may still be undiscovered classification of emergence. For example, an emergence that cannot described along must be different from an emergence that is inseparable from another emergence, i.e., the emergence of concept and the emergence of language. Besides, in some problems, emergence come from a single kind of basic components, whereas in other scenarios, emergence come from a combination of different kinds of components. These issues will be explored in the future.

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