Natural Emergence

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Emergence is analyzed by the principle of least action. The supreme law of nature describes diverse systems as actions that evolve from one state to another by consuming free energy in least time. As the system will either gain or lose quanta at the step of evolution, the systemic characteristics after the change of state cannot be reduced to those before the change. The change will invariably entail also a change in inter-actions, which are flows of energy on paths that integrate ingredient systems to a synergistic system. New qualities will emerge along with opening interactions just as old ones will disappear along with ceasing interactions. The analysis of emergence as a natural process reveals that its irreducible and unpredictable nature does not result from complexity as such but because the natural process itself is molding the surroundings where it is evolving.

Key Words: dissipation; eigenmode; entropy; evolution; free energy; the principle of least action

INTRODUCTION

The concept of emergence, despite its frequent use, remains ambiguous without consensus about its definition and fundamental nature [1]. The sudden appearance of a novel property is abundantly exemplified in current discourse but the process itself is not rigorously analyzed using concepts of physics. In fact, physics is regarded by many exclusively as a reductionist account thereby being incompetent to provide a holistic description of nature. However, we argue that when entities of nature at diverse levels of its hierarchy are properly described as actions, that is, energy densities in motion on their characteristic paths, emergence can be analyzed and understood as a natural process. New properties will emerge and old ones will disappear when actions combine with actions or disintegrate from each other either by acquiring quanta from the surroundings or by loosing quanta to the surroundings. This resolution of emergence as a physical process follows from the principle of least action [2]. The universal law of nature describes systems within systems in evolution by least-time consumption of free energy.

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THE NOTION OF ACTION

In physics, a system is characterized by its action. The attribute integrates energy over time or equivalently momentum along its path. For example, a metabolic system of a cell can be described as flows of energy over

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characteristic times that elapse when substrates move along reaction pathways. Also the photon that carries momentum on its wavelength is an action. In fact, it is the absolutely least action comprising only a single quantum. Undoubtedly, it would be in practice impossible to announce the precise number of quanta that constitute a large and complicated system. Nevertheless, the atomistic tenet of quantization is a comprehensive account. Most importantly it implies that any change of a system will invariably involve a change in its action at least by one quantum.

In general, the action of an evolving system accumulates different values along alternative paths [2] because different directions proffer the system with unequal numbers of quanta. In other words, the principle of least action in its original form [2] describes evolution as a nonholonomic process, that is, one having a history. Eventually, the system may attain a stationary state in its surroundings. At the free-energy minimum state, the action is at minimum. At the thermodynamic steady state, the system does neither gain nor lose quanta. Then, its conserved flows of energy are on optimal hence stable trajectories.

We are motivated to analyze emergence using the notion of action because the concept is comprehensive and scale-independent [3]. Moreover, it is associated with powerful theorems.

About a century ago, Noether connected conserved quantities and motional modes of a system with symmetry of its action [4]. Conversely, the prime statement of physics says that new qualities will invariably emerge and old ones will go extinct when the system changes its state of symmetry at least by one quantum of action. Noether's theorem implies that any entity of nature is ultimately composed of some integral number of quanta. Therefore, it is inescapable that when the system changes, it will either absorb at least one quantum from its surroundings or emit at least one quantum to its surroundings. According to Noether, the break of symmetry means that the motional modes that are characteristics of the system will change.

Absorptive processes are often deemed as self-organization where novel properties will be gained, whereas emissive processes are usually seen as disintegration where old attributes are lost. However, both processes obey the same inexorable principle that directs any system toward a free-energy minimum state in the respective surroundings. The consumption of free energy can be regarded as the sufficient reason [5] for a change of state or for a sequence of changes, that is, evolution [6]. For example, a chemical reaction, as any other transformation of identity, is either endergonic or exergonic depending whether the surroundings will supply the system with quanta or draw quanta from the system. This dissipative nature of emergence was exemplified a long time ago as follows: "The chemical combination of two substances produces, as is well known, a third substance with properties different from those of either of the two substances separately, or of both of them taken together [as a linear combination without reaction]" [7]. Also a phase transition is a dissipative event where at break of symmetry new qualities will emerge and old ones will vanish [8, 9].

Despite the apparent role of dissipation in emergence, much of contemporary physics is formulated to describe only stationary systems by imposing invariance, for example, by requiring that the energy content of a system is a constant or equivalently that the energy content of the surroundings is a constant. When the boundary conditions are fixed, there are no net flows of energy between the system and its surrounding; hence, there is no ambiguity in its trajectories. Then, the equation of motion can be solved, but the determined trajectory is that of stationary-state dynamics where nothing new will appear or old will disappear. By contrast, when the equation of evolution is written so that the net flows of energy between the system and its surrounding system are explicitly included, emergence of new properties will be understood as a natural consequence of the quanta that are either gained or lost.

IRREDUCIBLE DISSIPATION

Absorption or emission of at least one photon will suffice to open a new path for a flow of energy or to close an old one. The photons as force carriers are literally interactions, that is, quantized flows of energy that channel between the constituents of system (Figure 1). For example, during a chemical reaction electron orbitals of an atomic substrate will open either to acquire quanta from surroundings or to dispel quanta and close anew as molecular orbitals of a product. Thus, according to the physical portrayal of emergence [10], it is inescapable that the system will appear with new characteristics, when quanta from the surroundings integrate into the system's existing ingredients. Because of the energy input, the new qualities associated with new eigenvalues and eigenmodes are invariably irreducible to the former free constituents. Conversely, it would violate conservation of energy if any new property were to materialize from mere multiplicity, that is, from constant-energy permutations of pieces. Particularly, it takes some characteristic period of time for the system in a thermodynamic stationary state to traverse through all its configurations.

According to the physical portrayal of an evolving system, the emerging whole will indeed be greater than the prior sum of free constituents because quanta integrate from the surroundings to the system at the change of state. This was expressed effectively by Sir Arthur Eddington already a long time ago as: "We often think that when we have completed our study of one, we know all about two, because 'two' is 'one and one.' We forget that we still have to make a study of 'and'."—which is the photon.

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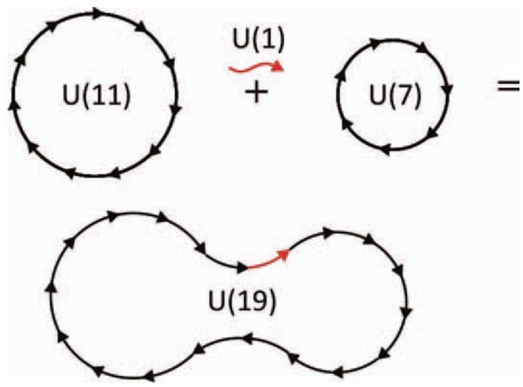
FIGURE 1



Systems are described as actions that belong to certain groups of symmetry. A change from one state to another is a change from one action to another. When the stationary actions in symmetry groups exemplified by $U(11)$ and $U(7)$ open up to include one quantum $U(1)$, the integrative step will amount to a change in quanta so that the action on closing will emerge with characteristics of $U(19)$. These novel properties cannot be reduced to those that characterize the symmetry groups of its ingredients. All real systems belong to some special unitary group SU(n), because energy bound in eigenmodes is positive.

This quantized description of emergence as a dissipative process from one state to another complies with conservation of total number of quanta in the system and its surroundings. It finds no need to classify phenomena to strong and weak emergence [11], but obviously the tenet recognizes that it will take period of time for each and every action to fully manifest itself in all characteristics of a system.

NATURAL SELECTION FOR LEAST ACTION

The break of one symmetry for another is a discontinuous dissipative event. The action can be either on a closed or on an open path but not on anything else. During the transition from one state to another, the flows of energy will consume free energy by the act of flowing from sources to sinks. According to the variational principle, the system does not know the optimal trajectory a priori, but the flows themselves are exploring alternative paths. Those paths that will consume the free energy in the least time will be selected by the flows themselves [12]. The least-time consumption of free energy is the natural bias that directs all processes toward free-energy minimum states. Along these dissipative trajectories, new properties will emerge and old ones will disappear. Eventually when all free energy has been exhausted, the flows of energy will settle on the paths of least action. These stationary flows manifest themselves as system dynamics.

According to the principle of least action [2, 10], biota has emerged and organized itself over the eons as the global food web in the quest for decreasing the difference between the high-energy insolation and chemical potential of substances on Earth [13]. A newly emerged quality is valued only as a means of energy transduction. Mechanisms, inanimate just as animate, will thrive when diminishing energy differences between the system and its surroundings. Those that will consume free energy in the least time are said to be the fittest [14]. Thus, complexity as such is no end itself, but an energy transduction network will organize itself from the available ingredients under the influx of energy to a complex system when that is more effective in decreasing energy differences with respect to its surroundings than a simpler system. For example, during ecological succession, the number of species as a measure of ecosystem's complexity often peaks before the climax state where a maximal consumption of free energy has been attained with fewer species [15].

In its entirety, the Universe evolves by stepping down from its current state of a higher symmetry to another of a lower symmetry by combustion of bound quanta to free photons in stars and other mechanisms [16]. A step down in free energy is a step forward in time [17]. Eventually, in the irreversible quest for the equilibrium at zero-density "surroundings," the lowest group of symmetry will be attained. When the system is described in terms of an action rather than only in terms of energy, the dissipative disintegration of a high-symmetry system is not destined to a troublesome singularity [18], but the process will eventually terminate to the lowest group of symmetry, $U(1)$, the photon itself whose momentum over its path length amounts to Planck constant. The notion of heat death [19] logically implies that every entity is ultimately composed of some integral number of photons [3].

Courses to complexity are customarily outlined by analytical functions such as logistic equation [20] and law of mass action [21]. Yet these forms are reticent in revealing causes, that is, that the energy differences that drive natural processes toward a free-energy minimum in the least time. Moreover, iterative maps [22] and self-organized criticality [23] are excellent models of symmetry breaking, but bifurcations and critical events are taciturn about the nondeterministic character of natural processes [24].

When the equation of evolution provided by the principle of least action is analyzed [10], it is found that the irreducible and unpredictable nature of emergence does not result from complexity as such, but the open trajectory among alternatives cannot be predicted precisely because the driving forces and flows energy cannot be separated from each other to allow integration of variational equation of motion to a closed form. As the natural process itself is molding the surrounding energy landscape where it is evolving, appearance of new properties as well as new

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species and disappearance of old ones are noncomputable phenomena. In other words, the evolutionary trajectories are nonholonomic paths because evolution itself is changing its settings, that is, boundary conditions. First, at the stationary state, the closed trajectories can be extrapolated by calculation, for example, by finding a unitary transformation that will make the system's time-independence explicit. Hence, it is the dissipation that makes the difference between emergence and extrapolation. This has been expressed effectively as "The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles" [25]. The interdependence of systems within systems, also referred to as supervenience, results from inter-actions that are the flows of energy, which integrate constituents to the entire entity.

CONCLUSION

Emergence can be understood as a natural process when entities of nature are described as actions that all are composed of some integral number of quanta. Then, the central connection between the symmetry of action and the qualities of a system, given in terms of conserved quantities and motional modes, can be analyzed mathematically to conclude that novel characteristics will emerge due to quanta that are either acquired or lost at a dissipative step of evolution. Conversely, no new qualities can appear in an isolated system or in a system that has attained a thermodynamic stationary state in its respective surroundings. The evolving system demands a holistic description whereas the stationary system suffices with a reductionist account [26]. The least-time consumption of free energy is the long-sought, albeit noncomputable, organizing principle [27]. The scale-spanning physical portrayal of emergence, despite being based on the supreme law of nature, may appear as a too simple account of sophistication to someone who is uninitiated in describing nature by physical materialism using mathematical formalism. However, the variational principle in its holistic form [10] does not reduce complexity to simplicity but renders emergence an analyzable and thereby comprehensible phenomenon.

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