On emergence from the perspective of physical science

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Abstract

In this paper, we summarize the development of the concept of emergence in physical science and propose key concepts of emergence in the form of conjectures. Our conjectures are threefold: I. A system having a broken-symmetry in membership relation with respect to micro and macro scales can have emergent properties. II. Spontaneous symmetry-breaking is an example of an emergent property. III. The phenomenon of hysteresis accompanies spontaneous symmetry-breaking. We argue that these conjectures and their relationship can illuminate the concept of emergence from the perspective of symmetry breaking.
1 Statement of the purpose

The purpose of this paper is to summarize the development of the concept of emergence in the field of physical science, with a few original propositions from the authors. Where the new propositions appear, we specify. During the review, we will formalize several propositions (some old and some new) regarding the concept of emergence in a form of conjectures. At the end, we restate three conjectures as the crucial propositions on the concept of emergence. Our view is informed by experimental examples in physics and constitutes a further theoretical study with respect to the New Emergentist Thesis advocated by Mainwood (2006). We begin with a description of the concept of emergence.

2 Definition of the concept of emergence

A property of a system is said to be emergent if it is in some sense more than the sum of the properties of the system’s parts. Emergence involves a process that exemplifies a higher-level, global property in relation to lower-level, local properties. Framed in terms of parts and wholes, one might say, along with Bar-Yam (1997), that "what parts of a system do together" would not be done alone were it not for higher-level, global properties. Thus an emergent (or higher-level, global) property, in our sense, makes a causal (and thus explanatory) difference to the way lower-level, local properties interact and function together.

3 Brief history: recalling Anderson’s paper

Modern usage of the concept of emergence began among philosophers and can be traced back to John Stuart Mill (1843) and George Henry Lewes (1875). The concept gained traction among philosophers, the so-called British Emergentism, and eventually culminated in Charlie Dunbar Broad’s (1925) seminal work, Mind and Its Place in Nature. However, in the field of science, with the success of the reductionistic approach throughout the 20th century, the emergentist view slowly retracted from the fields of physics, chemistry, and biology (McLaughlin 1992). As Mainwood observes:

"The sciences of the very small (for example, high energy particle physics) would be the one engaged in a search for fundamental laws, and other sciences could be in a sense derivative, in that their subject matters are ultimately the behavior of physical systems and this could be derived in theory from the laws and principles
that governed the very small." (Mainwood 2006, 3-4)

However, a significant change took place in 1972 that put emergentism back on the theoretical table, when Nobel Prize winning condensed matter physicist Philip Anderson published a short paper, *More is Different*. Anderson advocated the foundational concepts of emergentism in a pithy way as follows:

"At each level of complexity entirely new properties appear... At each stage entirely new laws, concepts, and generalizations are necessary... Psychology is not applied biology, nor is biology applied chemistry. We can now see that the whole becomes not merely more, but very different from the sum of its parts." (Anderson 1972, 393)

Thus, Anderson’s important paper rekindled the discussion of emergence once again among scientists, now summarized as the *New Emergentist Thesis*; and it is on these discussions that we focus our attention here.

4 Categorization of emergence

We first give an overview of possible kinds of emergence, primarily following and modifying the categorization of Christen et al. (2002). With exception of useful illustrations and analyses, all citations in the categorization below are from the aforementioned work by Christen and colleagues.

I. Epistemic Emergence: The phenomena appearing in the higher (upper) level is in principle reducible to the properties of the lower level entities. "The reason for the existence of a theory for the higher level is basically an instrumental one." (6)

II. Macroproperty Emergence/Laws Emergence: Some macroproperties (properties at the macroscopic level)/laws "appear on a higher level because their applications need a certain minimal degree of structure/organization." (7) In other words, these properties/laws are in principle only possible at the higher level because they require a certain minimal number of constituents interacting with each other. The interesting question in this case is "whether such properties/laws have the same status like the ones on the basic level." (7) We will assume for category II (unlike categories III and IV to follow) that higher level properties/laws will not *intervene* in the actions of the lower level entities. They are merely results of the large number of interacting constituents and do not have any say on the actions of constituents.
III. Weak Causal Emergence: Not only do there exist properties/laws at the higher level, it is also the case that the higher level properties/laws affect the lower level entities causally (downward-causation) in a way that the "possible causal space of the lower level parts (the in principle possible actions the parts could cause given the properties/laws of the lower level) is not violated" (7) In other words, the higher level properties/laws cause certain actions of lower level properties in a way that the lower level properties/laws are not violated.

For example, Nobel prize winning neuroscientist Roger Sperry became deeply dissatisfied with the essential concepts of behaviorism and reductive materialism in the 1960s and proposed a provocative emergentist alternative that sought to affirm our personal natures and to reassign a causal role to conscious properties within an evolutionary framework: "Instead of being excluded from science, subjective mental states, intrinsic to brains, are reconceived to be indispensable for a full explanation of conscious behavior and its evolution, and are given primacy in determining what a person is and does." (Sperry 1991, 222) However, what Sperry means by downward causation is a bit puzzling in certain passages of his work. For one thing, Sperry denies that the emergence of such properties could alter or supersede the laws that govern the relations of lower-level components (see also Hasker 1999). Although Sperry claims to be advancing a robust notion of emergentism, he nevertheless describes the relationship between micro-properties and macro-properties as a relation of supervenience:

"From the start I have stressed consistently that the higher-level phenomena in exerting downward control do not disrupt or intervene in the causal relations of the lower-level component activity. Instead they supervene in a way that leaves the micro interactions, per se, unaltered." (Sperry 1991, 230)

How can emergent conscious properties causally influence lower-level components if they cannot "disrupt or intervene" in the causal relations of those components? If Hasker and Meehl and Sellars are correct in asserting that the only way emergent properties can exert downward causal influence is by altering the laws that govern the relations of the lower-level components, then it might appear as though Sperry’s formulation of downward causation is incomplete

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1For a fuller view of Sperry’s approach to consciousness, see Sperry, Roger. 1952. "Neurology and the Mind-Brain Problem." American Scientist 40:291-312; Sperry, Roger. 1969. "A Modified Concept of Consciousness." Psychological Review 76:532-536; Sperry, Roger. 1970. "An Objective Approach to Subjective Experience." Psychological Review 44: 585-90; Sperry, Roger. "Mind-Brain Interaction: Mentalism Yes, Dualism, No." Neuroscience 5:195-206.
It seems clear that Sperry is committed to weak causal emergence with respect to conscious properties. Sperry illustrates such a commitment with a clever example involving the intermolecular relations of a rolling wheel:

"A molecule within the rolling wheel, for example, though retaining its usual inter-molecular relations within the wheel, is at the same time, from the standpoint of an outside observer, being carried through particular patterns in space and time determined by the over-all properties of the wheel as a whole. There need be no "reconfiguring" of molecules relative to each other within the wheel itself. However, relative to the rest of the world the result is a major "reconfiguring of the space-time trajectories of all components in the wheel’s infrastructure." (Sperry 1991, 223)

Despite its implicit advantages, there are nevertheless troubles that beset Sperry’s commitment to weak emergent conscious properties (WECPs). For one thing, there is an asymmetrical causal relation that holds between WECPs and base properties (BPs), such that WECPs require BPs for their instantiation but BPs do not require WECPs for their causal work. Elaborating the criticism more directly, even though Sperry’s rolling wheel analogue implies that WECPs could reconfigure lower level neuronal events, the explanation he actually provides (concerning the relationship between WECPs and BPs) ultimately entails the exclusion of WECPs as a source of causation. One might suspect that the reason for such exclusion is that, on Sperry’s account, the macro-level properties of the wheel, such as the property of going down the hill, are fully "explicable in the reductionist style, in accordance with ‘bottom-up’ microdeterminism" (Hasker 1999, 182; see also Kim 2000, 2005). Given Sperry’s allegiance to weak causal emergence, the lower-level BPs threaten to pre-empt any causal work that higher-level WECPs could play in one’s overall behavioral life. Rather ironically, for Sperry, consciousness turns out to be a fifth wheel with respect to behavior causation.

IV. Strong Causal Emergence: Now the higher level properties/laws change the possible causal space of the parts of the lower level. Not only is it the case that the properties/laws of the lower level alone cannot explain the action of the lower level entities, the properties/laws of the higher level precede those of the lower level causally.

For example, consider the hypothesis of strong emergent conscious properties (SECP). Under this hypothesis, SECPs are generated by the specialized activity of the

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²See also Meehl, Paul and Wilfrid Sellars. 1956. "The Concept of Emergence." in Minnesota Studies in the Philosophy of Science, Vol. 1: The Foundations of Science and the Concepts of Psychology and Psychoanalysis, ed. Herbert Feigl et al., 239-52. Minneapolis: University of Minnesota Press.
physical/biological properties, but are "not reducible to the physical-biological properties" in part because they are capable of exerting a "downward" causal difference (Varela and Thompson 2003, 273). In other words, the relation between consciousness and the brain is a reciprocal causal relation, from bottom-up causation to downward causation. The idea of reciprocal causal relations between the activity of neuronal assemblies and the activity of consciousness is consistent with dynamical systems theory, in the sense that SECPs could play a role of organizing, controlling, or constraining local neuronal activities (Varela and Thompson 2003, 273-275; see also Freeman 2000). Similarly, Kelso argues that consciousness "molds the metastable dynamic patterns of the brain" (1995, 288; see also Varela and Thompson 2003, 273-275).

5 So where does current emergence theory stand?

We note that there exists a fundamental difference between category I and the rest, in that from categories II to IV, there at least exist certain macroscopic phenomena which are impossible to reduce to the properties of the lower level. One of the aims of this section is to properly position the New Emergentist Thesis among the above categories. We will argue that the New Emergentist Thesis is, at least, not an instance of category I. Among categories II to IV, the difference comes from the status of the higher level properties/laws compared to those of the lower level. We will further try to position the New Emergentist Thesis among these three categories via Anderson’s approach to novel emergent properties.

Anderson (1972) motivates the novelty of emergent properties within a hierarchy of sciences, according to the idea that the elementary entities of science X obey the laws of science Y.

| X                          | Y                          |
|-----------------------------|-----------------------------|
| Solid state/many-body physics | Elementary particle physics |
| Chemistry                   | Many-body physics           |
| Molecular biology           | Chemistry                   |
| Cell biology                | Molecular biology           |
| .                           | .                           |
| Psychology                  | Physiology                  |
| Social sciences             | Psychology                  |

Then, Anderson goes on to state that "this hierarchy does not imply that science X is ‘just applied’ science X".

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"At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one."

(393)

If a macro-level, systemic property, X, is truly novel, then X and its governing laws could be regarded as exemplifying a reality status that is just as great as its micro-level properties and laws. Mainwood makes the following useful remark in this context: "some systemic properties are importantly novel: so different to the microphysical that they and the laws that govern them can be recognized as having a metaphysical status in no way inferior to the microphysical." (20)

For example, there exists a fundamental broken-symmetry, in the sense that parts in level Y are subsets of the whole system (at level X), but the whole system is not a subset of the parts in level Y. We name such a property hierarchical realism after Christen et al. (2002). In what follows, we conjoin hierarchical realism and novel emergent properties. To be clear, we first formally define those notions as follows:

I. Hierarchical realism: The system under consideration has at least two hierarchical levels, a higher level X where the system itself exists, and a lower level Y where the parts making up that system exists. There exists a broken-symmetry between the two levels, in the sense that the parts at Y are subsets of the whole system, but the whole system is not the subset of the parts. In set theoretic notations, we can write as the following:

\[ M = \{m_1, m_2, m_3, \ldots, m_n\}, \]

here, \( m_n \in M \) for \( n = 1, 2, 3, \ldots, n \),
but \( M \notin m_n \).

Here \( \in \) denotes a membership relation, where M is at the level X, and \( m_n \) are at the level Y. We can call this property the broken-symmetry in membership relation.

II. Novelty of emergent properties: Some properties/laws at the system level are novel, and different from those at the micro-level, such that they have the same reality status as the micro-level properties/laws.

Following Anderson, we maintain that novel properties exist at the macro level. This claim is at the heart the New Emergentist Thesis. Whether this claim is achievable will depend on its testability. We may restate the claim as a form of conjecture:

**Conjecture A (New Emergentist Thesis).** A system realizing hierarchical realism (having a broken-symmetry in membership relation) can have novel emergent properties at the macro level.
6 Novelty tests and their unsuitability

What are some possible methods for the novelty test and their unsuitability? Here we give two examples, one with a theoretic problem and the other with an empirical problem.

I. Failure of inter-theoretic reduction: Consider, for example, Howard’s (2002) reflection about a system with higher level B and in relation to the lower level:

"Inter-theoretic reduction is a logical relationship between theories. In the classic formulation owing to Ernest Nagel, theory TB, assumed correctly to describe or explain phenomena at level B, reduces to theory TA, assumed correctly to describe or explain phenomena at level A, if and only if the primitive terms in the vocabulary of TB are definable via the primitive terms of TA and the postulates of TB are deductive.” (3-4)

This method is about the relationship between two descriptions at each level, A and B of the same system; one description referring to microscopic properties of the system, the other to macroscopic. The ambiguity here lies in that the reduction from TB to TA will require some form of aids from the vocabulary of mathematics, and also in relation to the amount of description we allow in TA. If we allow only the first-order logic as the mathematical aid and also allow very little description in TA, then the method becomes too strict. Not many theories can be reduced from B to A. If we allow usage of many tools from mathematics as the aids in the reduction from TB to TA and allow vast vocabulary in TA, it will be possible to represent the British emergentism as inter-theoretic reduction. The problem of this method is that it is too general in its definition.

II. British emergentism: By contrast, C.D. Broad formulates an elegant definition of British emergentism in the following:

"Put in abstract terms the emergent theory asserts that there are certain wholes, composed (say) of constituents, A, B and C in a relation R to each other; that all wholes composed of constituents of the same kind as A, B and C in relations of the same kind as R have certain characteristic properties; that A, B and C are capable of occurring in other kinds of complex where the relation is not of the same kind as R; and that the characteristic properties of the whole R(A;B;C) cannot, even in theory, be deduced from the most complete knowledge of the properties of A, B and C in isolation or in other wholes which are not of the form R(A;B;C).” (61)
Broad also held that to derive the properties of a composite system from the properties of its components, the following is required:

"(a) We need to know how the parts would behave separately. And (b) we need to know the law or laws according to which the behaviour of the separate parts is compounded when they are acting together in any proportion and arrangement." (61)

The composite law in (b) can be either general or specific. If the law is universal in the sense that it can be applied to many other systems (such as law of vector addition for two vectors, which can be applied to any systems of vectors), it is called general. If the law is specific in the sense that it applies to only a specific system, and the law covers unique properties from that system, both the specific law and unique property are called emergent.

This approach focuses on the relationship between the properties of two different systems: one at the level of macroscopic scale (composite of the microscopic constituents), and the other at the level of microscopic scale (the constituents themselves). The problem surrounding Broad’s emergentism was an empirical one. At his time, no such specific laws were known to systems.

However, we remain optimistic that Broad planted the theoretical seeds for an updated version of British emergentism in the present. For one thing, Broad’s criteria for emergence represent well the intuitions of novelty and unexpectedness in current science. Broad recognizes that the properties of a composite system are always new in some sense. And as the lack of empirical data was the sole reason Broad’s criteria were set on the theoretical sidelines, we now give examples of symmetry-breaking and phase transition, which have been extensively studied experimentally and theoretically for the past several decades.

7 Possible examples for emergentism: I. ‘symmetry-breaking’ as a physical example of novelty producing process

In what follows, we present an example of a novelty producing process well studied in the physical sciences, that of ‘symmetry-breaking.’ After all, symmetry-breaking is the principal example Anderson (1972) presented as the novelty producing process in his seminal paper:

"In my own field of many-body physics, we are, perhaps, closer to our
fundamental, intensive underpinnings than in any other science in which nontrivial complexities occur, and as a result we have begun to formulate a general theory of just how this shift from quantitative to qualitative differentiation takes place. This formulation, called the theory of ‘broken symmetry’, may be of help in making more generally clear the breakdown of the constructionist converse of reductionism.” (393)

We focus on spontaneously broken symmetry (as opposed to explicitly broken symmetry, where some symmetry-breaking term is explicitly added into the equations governing the system: for example, consider an external magnetic term toward a particular spatial direction). It is defined by Anderson (1984) in the following manner:

"Although the equations describing the state of a natural system are symmetric, the state itself is not, because the symmetric state can become unstable towards the formulation of special relationships among the atoms, molecules, or electrons it consists of." (265)

Before we proceed to explain Anderson’s definition, it is important to state the principle of minimum energy: for a closed system with constant external parameters and entropy, the internal energy will decrease and the system will ultimately approach the state with a minimum energy at equilibrium. This is a restatement of the second law of thermodynamics, stating that in every real process the sum of the entropies of all participating bodies is increased. This principle is an empirical finding accepted as an axiom of physics. The fact that this is an axiom/law by itself without any derivation from other axiom/laws is important and will be emphasized later.

Now we will explain the terms in Anderson’s definition. Let’s assume that in our physical system of interest, that there exist governing equations which can describe the dynamics of the system and describe the possible states the system can possibly be in (e.g., in physics such governing equations for the system are often called Hamiltonian or Lagrangian of the system). For example, if such governing Hamiltonian/Lagrangian does not show any preference of the spatial orientation for the system to be in (e.g. the equation does not tell the system to align toward top direction or bottom, or to point left or right, or toward you or against you), then the equations have symmetry with respect to the spatial orientation, and are said to be symmetric under the operation of translations. The system, indeed, can take advantage of such symmetry and be in such a symmetric state.

In nature, we can observe the phenomena of ferromagnetism. For a ferromagnetic system (a system with very many ferromagnets) at high temperature, each individual component making up the system has random orientations like Figure 1 (a). Indeed, for such ferromagnetic
systems, the model equations we use to describe them have orientation symmetry. The interaction terms in the equations do not have any preferences for the orientations. However, at low temperatures, a novel phenomenon appears: *the symmetry of the system suddenly breaks down*. Under a critical point called Curie temperature, there appears stable states with individual components all aligned along a particular direction, as shown in Figure 1 (b). Now the newly aligned states have the lower energy compared to the symmetric random state; therefore, they become stable according to the principle of minimum energy, and the random state with symmetry becomes an unstable state, for it has higher energy.

What we observed here is one example of phase transition. Such phase transitions can happen not only in a system consisting of many magnets. It can also happen in a system with many H2O molecules, He molecules, and super conducting materials, among many others. In a system of H2O molecules, under the critical point of zero degree Celsius, the system now turns into a crystal called ice, by aligning in a particular pattern of lattice-like configuration. Above that temperature, the system gains symmetry (and becomes water) and the molecules freely move without any alignment and configurations.

In summary, the symmetry of a large system can be very different from the symmetry of the Hamiltonian of the system. The Hamiltonian, describing the interactions and motions of the individual, does not tell what kind of symmetry the system will have. We needed another law to
tell you that: the minimum energy principle. Thus, restating Anderson’s definition of spontaneous broken symmetry, "although the equations describing the state of a natural system are symmetric, the state itself is not, because the symmetric state can become unstable towards the formulation of special relationships among the atoms, molecules, or electrons it consists of." (265)

We summarize the traits of the spontaneous symmetry-breaking of a large system from the critical phenomena of the phase transition:

I. The system must be made of a very large number of individual components.

II. In our example, the components were homogeneous (this happens to be an unnecessary condition for phase transition: indeed, studies in physics tell us that much richer phenomena at the macro level are possible if the components are inhomogeneous).

III. There is a critical point where the symmetry of the system begins to break.

IV. Beyond the critical point, the Hamiltonian that was able to describe the macro-properties of the system loses its ability to describe.

V. We needed another law – especially the minimum energy principle – to describe the macro-properties/laws of broken symmetries in the large system.

We emphasize that the law we required to explain the broken symmetry appears beyond the critical point for the large system, which is the minimum energy principle. This is an axiom in physics, inspired by empirical findings. By the definition of axiom, it does not require any other laws to derive itself. In such manner, this exists independently from the microscopic laws. We can state that the macroscopic property/law of broken symmetry relies on the minimum energy principle that is not determined from the symmetries of the original Hamiltonian (arising out of the microscopic interactions). Therefore, the third essential claim of emergence, "novelty of emergent properties", that some properties/laws at the system level be novel and have the same status as the micro-level properties/laws, is satisfied. There may be cases that, upon close inspection, the microscopic interactions and laws that make up the Hamiltonian also rely on the minimum energy principle. Still, in such a case, both the macroscopic law and microscopic law will be at the level of status, and novel in the sense that the descriptions from the minimum energy principle at each level are different from each other.

The direction or alignment of the system, under critical point, can be different from system A to system B, even if their microscopic components are the same. For example, the ferromagnets can align toward top, like Figure 1 (b), or bottom, depending on the ‘slightest
difference’ in the initial arrangement of the magnets before they enter the Curie temperature. The question is, can we predict the alignment of the system if all the microscopic laws and information are known? We will return to this point later.

We summarize Anderson’s argument for the spontaneous symmetry breaking being the example of emergence as the following conjecture:

Conjecture B (Anderson’s Thesis): Spontaneous symmetry-breaking is a novel emergent property at the macro level, which cannot be explained from the laws/properties at the micro level.

8 Possible examples for emergentism: II. can ‘hysteresis’ be another example?

We now focus on another phenomenon, hysteresis. Again, it is a phenomenon associated with phase transition. In the broadest sense, hysteresis is a phenomenon where the current state of the system depends on its past history. The most popular example is again of the magnets (ferromagnetic materials), now in the presence of the external magnetic field.

For example, for a large ferromagnetic system made of many small magnets, consider the case where the temperature is low enough such that the aligning of the magnets reduces the energy, and such that in its natural circumstances the magnets are all aligned in one direction. Now we can apply an external magnetic field to the aforementioned system. As shown in Figure 2, when the external field is strong enough, all the magnets in the systems align in one direction, following the direction of the external field (A and B in Figure 2). When we reverse the direction of the magnetic field, the magnets in the system will now reverse its direction, and if the field is strong enough, all magnets will be aligned towards the opposite direction. During the process, the system itself acts as if it has inertia, and tends to stay where the system was at its previous stage. The arrows in the Figure 2 show such a history dependent path of the system. The dark area within the path is called hysteresis loop, and this area is the measure of the hysteresis for the system. Because of such path dependency, the system can be in either state C or D with exactly the same external magnetic field, temperature, pressure, etc.

The Phenomenon of hysteresis is another example of symmetry breaking. Here, the broken symmetry is with respect to the time. Laws governing physical objects usually have symmetry with respect to the direction of time, as we find in Newton’s law of motion describing the trajectories of moving objects. For example, when one throws a ball into the sky and makes a film of the trajectory, there is no way to know even if the film is projected in the time reversed order: Newton’s law predicts that the motion of the ball going up is exactly opposite of the
Figure 2: A system of magnets under external magnetic field exhibiting a hysteresis loop is shown. At point A and B, the magnets are aligned in the direction of external magnetic field. When the external magnetic field is changed, the system will either go through state C or D depending on its previous state.

motion of the ball going down. So, if you project the film in the rewound fashion, it will be as if it is shown in the original time direction.

That is not the case with the phenomenon of hysteresis. When one begins at point A in the Figure 2, you must pass the upper path going through C to reach B. When one starts from B, one must pass the lower path through D to comeback to A. If one films the action and projects it, it will be immediately noticeable if the film is shown in reversed time direction.

Yuri Mnyukh argues from his paper (2013) that the phenomenon of hysteresis is a universal feature (at least) in the phase transitions of condensed matters. Mnyukh argues that the mechanism of phase transition is nucleation and propagation in most, if not all, cases, and it inherently features hysteresis as one of its characteristics. If Mnyukh’s argument is correct, then hysteresis (thus, time symmetry-breaking) would be a common feature of condensed matter phase transition, including the spontaneous symmetry-breaking example given in Section 7. We summarize Mnyukh’s argument as the following conjecture:

Conjecture C (Mnyukh’s Thesis): Hysteresis (time symmetry-breaking)
accompanies all phase transitions, thus also the one caused by the spontaneous symmetry-breaking.

If Mnyukh’s thesis is correct, then proving that the hysteresis is a novel emergent feature, will be equivalent to proving that the spontaneous symmetry-breaking is a novel emergent phenomenon. This is because the phenomenon of hysteresis always accompanies spontaneous symmetry-breaking phase transitions.

9 Emergence and its relationship to symmetry-breaking: Curie’s principles

We begin this section by restating three conjectures:

**Conjecture A (New Emergentist Thesis):** A system realizing hierarchical realism (having a broken-symmetry in membership relation) can have novel emergent properties at the macro level.

**Conjecture B (Anderson’s Thesis):** Spontaneous symmetry-breaking is a novel emergent property at the macro level, which cannot be explained from the laws/properties at the micro level.

**Conjecture C (Mnyukh’s Thesis):** Hysteresis (time symmetry-breaking) accompanies all phase transitions, thus also the one caused by the spontaneous symmetry-breaking.

We point out that these conjectures are related to each other. Proving Conjecture B will essentially prove Conjecture A – that there exist novel properties at the macro level. Proving Conjecture C may make the task of proving Conjecture B easier: proof that hysteresis is a novel emergent phenomenon is enough of a proof for Conjecture B.

These conjectures look at the problem of emergence from the perspective of symmetry breaking. The New Emergentist Thesis essentially becomes the question of whether symmetry-breaking in membership relation causes spontaneous symmetry-breaking (or time symmetry-breaking) in the system at the macro level, which cannot be explained from any other laws/properties at the micro level. Upon answering such questions, we may take hints from principles stated by Pierre Curie, the very person who contributed to the study of systems in Section 8 and Section 9, and came up with the concept of Curie Temperature. We recite Curie’s principle of symmetry properties from Brading and Castellani (2005, 4):

1.1. When certain causes produce certain effects, the symmetry elements of the causes must be found in their effects.
1.2. When certain effects show a certain dissymmetry, this dissymmetry must be found in the causes which gave rise to them.

1.3. In practice, the converses of these two propositions are not true, i.e., the effects can be more symmetric than their causes.

2. A phenomenon may exist in a medium having the same characteristic symmetry or the symmetry of a subgroup of its characteristic symmetry. In other words, certain elements of symmetry can coexist with certain phenomena, but they are not necessary. What is necessary, is that certain elements of symmetry do not exist. Dissymmetry is what creates the phenomenon.

Logically, 1.1 and 1.2 are the same, and 1.3 clarifies the statement. The effects may be more symmetric than the cause, because the dissymmetry does not necessarily have to be transferred from the cause to the effect. However, if there is a dissymmetry (broken-symmetry) in the effect, there must be a dissymmetry in the cause. Essentially, the claim of New Emergentist Thesis is that such cause of dissymmetry is not in the micro level laws/properties, but in the macro level laws/properties, which originating in turn from the dissymmetry in the membership relation between micro and macro. Do we have enough confidence about these conjectures such that they can be considered an experimentally and/or theoretically proven thesis? We hope to discuss this question in future works, also providing a clearer relationship between broken-symmetry and emergence in the course.

10 Epilogue

There is a fundamental question about the novelty of emergence related to the very nature of science. At its heart, science is crucially tied to an inductive mode of reasoning. Every theory is based on natural observations, and the aim of every theory is to explain and predict the natural observations. The validity of a theory is confirmed by experiments, and a theory is valid only if the next experiment correctly confirms it so. As Karl Popper puts it, every scientific theory should be falsifiable by the next experiment. There is Renormalization Group (RG) Theory in the field of statistical physics which may explain some examples of critical phenomena of phase transition. At the heart of the theory, there exists an iterative process called renormalization by which we draw out macroscopic variables from the microscopic ones. According to the theory, for the group of systems in the same category called universality class, the microscopic details of the systems does not matter in drawing out the macroscopic properties. It may very well be that the theory is self-consistent and without any loopholes, such that we can prove the novelty at the macroscopic level and therefore the existence of emergence with the theory. RG does not need to be a sole theory for such a task as explaining
the mechanism for the emergence in question. We can construct many other theories, which explain natural phenomena fittingly; and at the same time explains the mechanism for the emergence under investigation. However, there is always a chance that the theory may be falsified by our next experiment. We need theories to observe and explain the phenomena of nature, and there is never a guarantee that any of those theories will be correct forever. In this respect, the proof of novelty and claim of emergence is always epistemic (with the possibility of being ontological). But by all practical means, in so far as our theory at hand is not wrong yet, we can assume that the claim of emergence is ontological, at least given what we know today.
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