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Emergent phenomena

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Abstract. The paper presents the main philosophical and scientific concepts which are suggested in order to describe emergence. Grounded on the stratification of the universe in organizational levels, it characterizes and classifies the emergent phenomena. It proposes three couples which specify the emergence modes: unilateral vs. bilateral, synchronic vs. diachronic, mindless vs. mindful. It finally analyzes some classes of formal models able to explain through different disciplines the emergence process.

1. INTRODUCTION

An emergent phenomenon is a macroscopic structured phenomenon which seems to result from microscopic interactions, but cannot be easily explained by the modeller. Emergent phenomena appear at all organizational levels of the universe from the particle one to the social one through the organic one. Some of them have a large scope and seem really unpredictable, especially the apparition of life, of conscience or of language. Some are more local and less surprising like dune shapes, crystal structures, vegetal forms, animal societies or money kinds.

On the one hand, following the *British emergentists*, philosophers consider that some phenomena are intrinsically impossible to reduce to simpler elements. On the other hand, according to their many successes, scientists consider that some phenomena may well resist to reduction, but only provisionally. This article presents the arguments attached to both positions and tries to establish a bridge between them. It describes successively the kinds of emergent phenomena, the types of emergence processes and the classes of explaining schemes.

2. TYPES OF EMERGENT PHENOMENA

2.1. Organizational levels

The ontology of the universe is traditionally conceived as stratified into nested organizational levels. Each level is characterized by some prototypical entity endowed with specific properties and related to similar or different ones. The micro-entities associated to a lower level combine in order to form a macro-entity of the upper level. One considers usually the physical level (atoms), the chemical level (molecules), the biological level (cells), the physiological level (organs/tissues), the psychological level (organisms/individuals) and the social level (communities).

Two major problems of distinction or delimitation between the successive levels may take place. On one side, two non adjacent levels may be directly linked by considering some shortcut relations. For instance, a biological organism may be directly analyzed as a set of undifferentiated cells without making explicit any intermediary organs. On the

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other side, two adjacent levels may be articulated thanks to some intermediary permanent structures. For instance, molecules gather first in colloids or in crystals and individuals in union trades or in towns.

Moreover, there exists a description language developed by the modeller and adapted to each level. The set of concepts which characterize a specific entity of some level is only partially significant at some other level. For instance, an atom is not altruist, the brain is not crowded, the individual is not malleable and money is not sweet. This irreducibility statement already characterizes some special kind of emergence called ‘nominal emergence’. In each discipline, the relevant concepts are considered as theoretical or observable, even if the first may be revealed from the observation of the last.

For the observable concepts, specific investigation techniques are designed and used at each level. These techniques act more or less profoundly on the system itself and may well perturb the measurement process. For instance, charged atoms are detected by an ammeter, molecules by chemical tests, cells by microscopes, brains by cerebral images, individuals by questionnaires and societies by statistics. The observer observes through human senses in a middle range, but is informationally above the physical and biological levels and beneath the social level.

2.2. Microscopic level

The microscopic level is formed of three basic elements, the entities, their relations and the global context. Each of these elements is categorized in specific taxonomies and gives way to specific laws involving frequently stochastic factors. These microscopic regularities are indeed assumed to be independent of the macroscopic level. But some local elements are influenced by the whole system and can even not exist without it. For instance, if some molecules may be considered in isolation, only special cells or special individuals may be considered as not already socialized.

The *entities* are endowed with intrinsic properties which characterize their belonging to well defined classes of objects. They are also endowed with extrinsic properties which differentiate different kinds of these objects and qualify their heterogeneity. For instance, metals are globally characterized by their brilliance and conductibility and are discriminated by their voluminal mass or their coefficient of dilatation. Either physical or psychical, the entities obey to ‘laws of repartition’ expressing the distribution of their extrinsic properties in a given population.

The *relations* between entities may design a permanent and exogenous substratum on which these entities are scattered. These bilateral or multilateral relations may also generate an endogenous and temporary network between entities. For instance, molecules are trapped in a previous crystal and simultaneously linked together by other relations. The relations can be sub-induced by some prior properties of the entities or be autonomously defined as the result of their behaviour. Either material or informational, the relations satisfy ‘laws of interaction’ acting in an ‘interaction neighbourhood’.

The *global context* is first formed of a ‘surrounding environment’ with which the entities hold external relations. It is moreover formed of an ‘encompassing environment’ constituted by macroscopic entity to which the entities may belong. For instance, a cell is influenced both by external factors and by the pressure of the overall organism. The surrounding environment is not micro-reduced and the external relations are generally less dense than the internal ones. Either material or institutional, the global context imposes some constraints summarized in ‘context laws’.

2.3. Macroscopic level

At the macroscopic level, some salient patterns may appear and are captured by the modeller’s recognition tools. They are described either in the terms of the microscopic level or in terms specific to the macroscopic one. Especially, some properties of the entities or relations which are relevant at each level may be reversed when evolving from a lower to an upper level. Discontinuity switches to continuity, reversibility to irreversibility, stochasticity to determinism, symmetry to asymmetry. Three types of emergent phenomena may be considered according to their degree of originality.

Statistical phenomena consist in regular distributions associated to specific properties of the entities. A single property already gives rise to a given distribution, eventually supported by a permanent network of the entities. For instance, the luminous points in an interference scheme manifest coronas while the revenue distribution in an economy obeys the Pareto law. Two properties are related by a given relation, especially a scale law relating some overall property to the size of the entities in a population. For instance, the frequency of words in a language is related to their length or the performance of towns in a country to their population.

Structural phenomena consist in endogenous networks formed by the relations linking the entities. These relations may form static patterns of different shapes such as circles, stars or hierarchies. For instance, the atoms are linked through different patterns (spirals, ribbons, Turing structures), while the sellers and buyers of a product define stable fidelity relations. These relations may also lead to dynamic chains of different structures such as cycles or trees. For instance, cycles appear in the synthesis of proteins, the life of a cell, the development of an organism, the evolution of the climate or the development of an economy.

Qualitative phenomena consist in the genesis of original properties or even of autonomous entities (‘holons’). They appear as innovative traits resulting directly at the macroscopic level from the microscopic apparent desorder. For instance, one observes the genesis of Bénard cells in a liquid, of visual systems in an organism or of social norms in an organization. Moreover, these properties or entities vary more or less continuously when the microscopic elements change. For instance, one observes phase transitions between states of a fluid as well as regime modifications between states of an economy.

2.4. Emergent phenomena

Emergent phenomena are macroscopic phenomena which are assumed to be issued from microscopic elements, but obey moreover to additional features. These additional features always refer to the difficulty to conceive some macroscopic properties or relations as issued from microscopic ones. In the philosophical literature, a ‘resultant property’ is considered as easy to derive from more basic elements unlike an ‘emerging property’ (Mill). While the levels of organization can already be considered as either ontological or epistemological, the same is true for the emergent phenomena.

Ontological emergence assumes that the emerging phenomenon is a realistic feature of some macroscopic object. It is considered as an objective phenomenon even if it only can be perceived and isolated by an outside observer. A spatial defining feature is ‘salience’, which means that the phenomenon manifests some autonomy. A temporal defining feature is ‘persistence’, which means that the phenomenon manifests some durability. A third defining feature is ‘resilience’, expressing that the phenomenon is robust to some variations in the microscopic elements.

Epistemological emergence assumes that the emerging phenomenon is just an explicit statement of the modeller. It is considered as a subjective phenomenon since it depends on the conceptual capacities of the modeller. A strong defining feature is ‘predictibility’, which means that the modeller is able to expect it ex ante. A weaker property is ‘explainability’, which means that the modeller is able to give it an ex post explanation. Of course, such an explanation may be considered as achievable in principle (with unbounded cognitive capacities) or in fact (with present or future cognitive capacities).

In any case, the explanation of an emergent phenomenon appears as a ‘reduction’ of the phenomenon to microscopic elements. The reduction is ontological when one organizational level is considered as resulting from more primitive ones. For instance, the psychical traits attributed to conscience are considered as resulting from the material functioning of the brain. The reduction is epistemological when some upper level theory is considered as the conceptual result of lower level ones. For instance, the behavioral traits attributed to living beings are considered as the result of physical laws.

3. TYPES OF EMERGENCE

3.1. The emergence problem

A macroscopic phenomenon is explained by the properties of the entities, by their relations and by the global context. In fact, some elements may be useless (especially the context) or at least receive less weight than others (properties versus relations). An emergent phenomenon is assumed to be ‘multi-explicable’, which means that it can be justified by several combinations of microscopic elements. This is captured by the concept of ‘supervenience’, which expresses that the microscopic elements are sufficient but not necessary to obtain the emergent phenomenon.

In fact, the main challenge is to change the ‘horizontal relations’ between microscopic entities into ‘vertical links’ between successive levels. This is of course an epistemological operation achieved by the modeller and acting on concepts as well as laws or models. The horizontal relations are assumed to have a material (or not) ontological basis, even if they are expressed as conceptual laws linking some variables. The vertical links are immediately conceptual since they are constructed from the preceding ones, but may nevertheless be qualified as material (or not) if the underlying relations are so.

The idea of ‘self-organization’ refers to a spontaneous process achieving an emergent phenomenon without any external intervention. It opposes the idea of ‘designed organization’ which refers to a controlled process achieving an emergent phenomenon by means of an external planner. For instance, a watch, a new molecule or a new financial market may result from a voluntary emergence or a mixed one. Only spontaneous emergence will be considered from now, and it carries with it the whole ‘self galaxy’ (self-replication, self-reparation, self-reproduction).

The notion of self-organization is associated with the notion of complexity applied to the macroscopic system. The system is structured around numerous and heterogeneous entities linked by various and entangled relations. The system develops non linear and stochastic interactions which generate positive (amplifying) and negative (stabilizing) feedbacks. The system evolves under different driving forces and manifests context-dependency as well as history-dependency. The transitory states may be constantly renewed or give rise to asymptotic ones characterized by regular patterns.

3.2. Unilateral and bilateral emergence

The links between two successive organizational levels follow two directions, bottom up and top down. According to the existence of only the first link or of both, one speaks of unilateral or bilateral emergence. The first ensures the integration of the microscopic entities governed by their relations and their surrounding environment into a macroscopic system. The second ensures the regulation of the microscopic entities exercised by the macroscopic system acting as an encompassing environment. These two links are generally considered as acting independently on the system even if they are concretely coupled.

In order to construct the bottom up relation, the modeller introduces ‘bridge principles’ over variables. A macroscopic variable is defined over microscopic ones by some aggregation procedure (summative or else). For instance, the temperature of a gas is defined as the average kinetic energy of the constituting particles while the total consumption in an economy is the sum of the individual ones. The epistemological status of a bridge principle varies from a conventional definition (if only the upper variable is measurable) to an empirical law (if both variables are measurable).

The same bridge principles allow now to turn microscopic relations into macroscopic ones along a ‘rectangular scheme’. At lower level, some microscopic (explaining) variables entail a microscopic (explained) one. Between two levels, bridge principles relate the microscopic variables to corresponding macroscopic ones. At upper level, by eliminating the microscopic variables, some macroscopic (explaining) variables entail a macroscopic (explained) one. For instance, the Boyle-Mariotte law can be recovered from the laws of gas kinetics while the macroscopic consumption law can be derived from the microscopic ones.

The open problem is to construct a top down link which acts simultaneously with the bottom up one. The rectangular scheme does not allow this since the bottom up link is just the result of an aggregation procedure. The horizontal relations at the microscopic and at the macroscopic levels state the same laws in different terms (in average). The only possibility is to consider that new relations appear in some indirect way without assuming a double determination. A macroscopic variable may influence directly a microscopic one without transition through another explaining variable.

3.3. Synchronic and diachronic emergence

The links between two successive organizational levels depend generally on time in different ways. Emergence is ‘synchronic’ when the link holds instantaneously and ‘diachronic’ when it is delayed. In the first case, the microscopic elements are active at any time and coexist for a long time with the macroscopic phenomenon. In the second case, the microscopic elements construct progressively the macroscopic phenomenon and may even disappear after some delay. But a phenomenon produced by diachronic emergence can also get progressively stabilized and seems to be obtained by a synchronic one.

In order to deal with time, the modeller has to define a time scale for each variable according to its speed of evolution. The simplest case considers one time scale obtained with two types of variables: the fixed ones and the variable ones. Two time scales need to consider three types of variables: the fixed ones, the slow ones and the fast ones. In biology, the cells develop and are renewed at short term while the whole organism evolves at long term. In economics, the firm fixes prices and quantities at short term and modifies technologies at longer term.

The relations have a time dependence which is defined in accordance with the time scales of the constituting variables. When two time scales are considered, a short term relation expresses how the fast variables influence one another conditionally to the values of some slow and fixed ones. A long term relation expresses how a slow variable varies with the other slow variables as well as with the fixed ones. In discrete time, a short term relation shows how a fast variable varies in each period while a long term relation shows how a slow variable varies between two periods.

In concrete systems, it is often possible to observe a correlation between the organizational links and the time scales. A bottom up relation acts essentially in the long run while a top down relation acts rather in the short run. For instance, the production of cells constructs progressively the whole organism, but the last controls instantaneously the production of cells. The activity of a firm on the market induces an incremental change of shared technologies, but the feedback of technologies on the offers of the firm is fast. Hence diachronic emergence seems to be the rule and synchronic emergence appears as an exception.

3.4. Mindless and mindful emergence

The link between two organizational levels may be of different nature, namely physical or psychical. Emergence is mindless when the links are purely causal and is mindful when some links are informational. In the first case, purely material interactions between microscopic entities lead to similar links between levels. In the second case, the entities of the lower level are able to have representations of the organizational structure and functioning. Of course, the agents perceive some material facts, but these representations modify retroactively their behaviour.

The notion of information is precisely defined only in a social setting and -associated with the notion of knowledge- is twofold. By intentionality, an individual represents the physical environment which surrounds all of them. By specularity, an individual represents the others' representations of the environment and so on. For instance, an individual has some representation of the economic system and a representation of the others' representations of it. In fact, the notion of information can already be metaphorically introduced in biology (as an ability to produce) or even in chemistry (as an ability to recognize).

The qualitative nature of the organizational links is strongly related with the direction of these links. The individuals are frequently able to represent the microscopic entities and relations surrounding them. But they are seldom able to represent the emergent phenomena they are contributing to construct. The 'unexpected' phenomena are precisely joint results of the actions of several agents which fall out of their scope. For instance, a financial bubble may appear on some market without being perceived or at least not being attributed by them to their behaviour.

In the same way, the qualitative nature of the organizational links is related with the time scales. The individuals may be directly aware of the emergent phenomenon they are building together. But they may also recognize its true nature and its origin with some delay and act in consequence. Each agent progressively analyzes the phenomenon as some autonomous device exogenously driven and reacts now directly to it rather than to the others' actions. For instance, if a queue forms spontaneously at some place, it is recognized as such and is followed by all newcomers.

4. EXPLANATIONS OF EMERGENT PHENOMENA

4.1. Equilibrium models

The first explanation defines an emergent phenomenon as some salient equilibrium state between microscopic entities. The emergence is bilateral since it rests on a feedback between the macro-properties and the micro-entities. It is synchronic since it corresponds to the fixed point of the loop relating variables at both levels. In physics, it is mindless since several particles interact according to fundamental laws defining a global field. In economics, it is mindful since buyers and sellers are influenced and coordinated by the prices of goods acting as an observed collective variable.

An equilibrium state appears as a stable state achieved by microscopic entities in the absence of any external perturbations. Considering time scales for variables, nested equilibrium notions can be defined, for instance short term and long term ones. As a consequence, a long term equilibrium state is obtained by convergence of a sequence of short term ones. In physics, a short term equilibrium state can be obtained in an open system (dissipative structures) and disappears at long term. In economics, short term equilibrium states appear when prices are fixed and long term ones when they adjust.

Two methodological problems are generally associated to the – essentially static – equilibrium notion. On the one hand, an equilibrium state is defined by stability conditions imposed by the modeller without making precise how it forms. The 'implementation problem' concerns the concrete process by which the equilibrium may be achieved. On the other hand, several equilibrium states may happen simultaneously, which violates the supervenience principle. The 'selection problem' concerns the choice of one equilibrium state when there exist a multiplicity of them.

In some cases, the behaviour at the macroscopic level can be derived from some function which is maximized by the system. The local relations between the entities of the system are replaced by a global function which reflects its 'potential'. An equilibrium state appears just as a local maximum of such a function, many of them being eventually available. In physics, the potential expresses the total energy of the system summarized in a Hamiltonian function. In economics, the potential expresses a collective utility of the system formalized in different ways.

4.2. Evolution models

The second explanation describes an emergent phenomenon as the result of conjointly selected microscopic behaviours. It is generally unilateral since the basic entities react only to other entities in their neighborhood. It is essentially diachronic since the system progressively modifies its own microscopic elements. It is mindless in biology where the species are assumed to evolve according to a Darwinian process. It may be mindful in economics where the agents are submitted to learning processes only based on their past observations (others' actions, own's payoffs).

Three main principles are involved by the biology-like evolutionary processes applied to specific entities. The 'variation principle' assumes that the entities are able to vary exogenously in some range. The 'selection principle' assumes that these entities are selected by competition with other similar entities. The 'transmission principle' expresses that the selected traits are carried up by the entities through time. Such a mechanism extends from biological phylogenesis towards lower levels (ontogenesis, chemistry) as well as higher ones (psychology, economics).

Two methodological problems are generally associated with this loosely defined 'universal' process. On the one hand, the principles are defined outside biology by using the Darwinian process in a metaphorical way. The 'metaphor problem' concerns the concrete process by which the entities bear mutation and selection in each practical illustration. On the other hand, some form of stochasticity is introduced for each principle, especially for variation. The 'prediction problem' asks how to expect the path of a system which is fundamentally context- dependent.

In order to make the process more precise, a notion of fitness attached to each entity is frequently introduced. The evolutionary process is then assumed to select the entities which are the fittest in the whole population. But fitness must be defined independently of the process itself in order to prevent self-reference acting as a paradox. However fitness may depend on the context provided that the way it is linked is known by the modeller. In many applications, especially in economics where fitness is confounded with utility, such a demanding notion is hard to obtain.

4.3. Dynamic stochastic models

A more general explanation describes an emergent phenomenon as the asymptotic state of some dynamic and stochastic process. It generalizes the two previous explanation schemes, but in an instrumental perspective generating the phenomenon rather than explaining it. The asymptotic state appears as an equilibrium state since no entity has a tendency to move in such a state. The dynamic process may be an evolutionary process when it is governed by specific principles. Such dynamical systems are introduced and studied at almost all organizational levels.

The global state of the system is formed of the concatenation of local states adopted by each entity and of the state of environment. Both state and time may be discrete or continuous, with formal possibilities of shifting from one to another. The relations between states reflect the relations between entities and are essentially non linear, dynamic and stochastic. The global state evolution manifests strong dynamic instability and is often submitted to bifurcations. It converges (stochastically) towards different kinds of 'attractors', either punctual or cyclic or chaotic.

Two main models are studied, with their main transitory or asymptotic properties interpreted as emergent. On the one hand, a 'differential system' allows to study by analytical ways some transitory or asymptotic phenomena. Especially, cycles of different origins can be obtained: internal/external, deterministic/stochastic. On the other hand, a 'cellular automaton' allows to study by computerized simulation some transitory macrostructures essentially. These structures are geometrical (planers) in the state space and need to be recognized as salient by the modeller.

By specifying the dynamical model, various semantic interpretations define subclasses of models. Each subclass is intended to explain a kind of phenomenon observed in different disciplines. Contagion models explain how some item diffuses through a population of entities, when each entity revises an adoption probability. Agglomeration models explain how entities progressively gather in a structured group, when each entity revises an adhesion probability. Coordination models explain how entities behave dynamically in order to accomplish some function.

4.4. Emergence and complexity

A macroscopic phenomenon appears as emergent when its complexity is high, preventing its reproducibility. Once it is formalized, some algorithmic criterion can then be used in order to measure its complexity. It refers to concepts already developed in computer science when characterizing the complexity of a formal object or operation. Such a definition appears as more objective than the judgment expressed by the modeller about the singularity of some phenomenon. But it stays nevertheless contextual to the sort of modelling of the phenomenon which is proposed.

Different measures are available, which express different features of the phenomenon (Delahaye). 'Stochastic complexity' evokes the incompressible informational content of the emergent phenomenon. It is the length of the shortest computer program able to produce it (Kolmogorov complexity). 'Organized complexity' evokes the unavoidable computational difficulty of the emergent phenomenon. It is the computing time of the shortest program which produces it (logical deepness of Bennett). The two measures of complexity do not vary monotically, hence have to be considered separately.

An emergent phenomenon is assumed to have a maximal complexity with regard to a class of phenomena. Maximal complexity happens when it is not possible to derive the phenomenon without simulating entirely the behaviour of the underlying system. There is no shortcut by which the phenomenon can be generated except by computing its genesis step by step. For instance, a cell cannot be conceived without going trough the whole evolution process. Likely, the structure of prices cannot be guessed without comparing the offers and demands on all markets (von Hayek).

However, such a definition appears as neither necessary nor sufficient when compared to common sense. A phenomenon which shows a high complexity index may not look emergent at all for the modeller. For instance, the fall of a leaf is an unpredictible phenomenon which is very sensible to many influences, but does not appear as emergent. Conversely, a phenomenon which seems truly emergent may not appear as maximally complex. For instance, the structure of an eye seems very simple and similar to a camera, even if it needs a long and intricate evolution process.

5. CONCLUSION

The concept of emergence is not theoretically new since it just characterizes an original macroscopic phenomenon. It is strongly related to the old concepts of self-organization and complexity which were studied for a long time. But it is heuristically convenient since it obliges to relate a lot of methodological problems usually treated in isolation. It attempts to respond to the question of the apparently stable organization of the universe in nested levels. It stresses the fact that some phenomena are really hard to explain for various reasons, but are not mysterious so far.

There exists no general model of emergence which can be applied at any level of the organizational hierarchy. The integration of one given level into the next obeys to specific concepts articulated in specific laws. But some analogies nevertheless appear, leading to common classes of models studied once and for all. These models suggest standardized explanations of macroscopic features by microscopic elements. A precise taxonomy of such classes of models needs to be built, stressing in what sense the underlying analogy is substantive or only formal.

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