What is Emergence?

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A general theory of emergence should first start taking into account that this concept cannot be defined in an *objective* way. The word "emergence" refers to a relationship between an observer, the models which he is equipped with, and certain results of observations, or of measure operations, in turn dependent on his mental schemata and on his technological apparatuses. Therefore the emergence can be defined only *relatively to a given observer*, whose features should be specified in a suitable way. For the purposes of the present discussion we will assume that the observer is a theoretical physicist, endowed with all actual tools of this discipline and with the best computing facilities so far existing. This means that the emergence which we will speak of will be associated to some discrepancy between the forecastings, whose attainment was the goal of the models introduced by the observer, and actual behaviors evidenced within models themselves.

Once given such an intuitive definition of emergence, it allows for a number of further subcases and specifications. The best categorization of these latter appears the one given by Crutchfield (see Crutchfield, 1994; cfr. also Pessa, 1998). Here we will take into consideration, as the most interesting one, the subcase denoted by Crutchfield as *intrinsic emergence*. The emergent behaviors belonging to the latter category are associated to the following features:

1. they are *compatible* with the model used by the observer; for instance, they are solutions of model's equations or are produced by computer simulations of it;
2. their occurrence, however, *cannot be foreseen in advance* on the only basis of the adopted model;
3. they are *macroscopic*, that is their occurrence persists despite changes in the observational scale.

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Such features appear to be typical of most phenomena commonly classified as "emergent" and associated to the behaviors of many complex systems in the domains of physics, biology, economics, psychology, and so on. For this reason the study of this kind of emergence appears as one of the most important actual goals of Systemics.

To this regard, the first question to be answered is: do exist mathematical models allowing for intrinsic emergence? Happily, the answer is positive. Besides, these models can be classified into two main categories: the *ideal* models of intrinsic emergence and the ones which are *not ideal*. Between the main features of the former, we will quote the following:

a) they derive from general principles;
b) they work typically in a infinite volume limit;
c) they are focussed on ground states and on asymptotic limits.

On the contrary, not ideal models of intrinsic emergence are:

d) based on phenomenological considerations;
e) relying on the existence of suitable boundary conditions;
f) focussed on metastable states and on transient dynamics.

Between the ideal models of intrinsic emergence the most celebrated are the ones based on the mechanism of *Spontaneous Symmetry Breaking* (SSB) in Quantum Field Theory (cfr. Itzykson and Zuber, 1986); to the category of not ideal models belong, instead, neural networks, cellular automata, and all models of Artificial Life.

A second fundamental question is related to the delimitation of the class of ideal models. The importance of this question stems from the fact that, so far, the only models of emergence amenable to a rigorous mathematical analysis are the ones belonging to this class. Thus, ideal models appear as the only existing candidates for the building of a rigorous mathematical theory of emergence. To this regard we remind that a number of physicists (cfr. Anderson and Stein, 1985; Umezawa, 1993) made a very strong claim, which sounds like: *the only possible ideal models allowing for intrinsic emergence are the ones based on SSB in Quantum Field Theory.*

Here we will shortly present a number of points which constitute the rationale for such a claim:

- Quantum Field Theory is the only theoretical framework allowing for the existence of different representations of the same physical system, which are not unitarily equivalent one to another; this means that there exist qualitatively different descriptions of a same system which cannot be reduced one to the other, as they correspond to different "physics"; such a circumstance evidence how Quantum Field Theory is the only existing framework allowing for the existence of different *phases* of the same