

# Emergence of Simplicity and Complexity\*

Yaneer Bar-Yam

*New England Complex Systems Institute, Cambridge, MA 02139*

(Dated: September 16, 2018)

In our explorations of the world we have often discovered that the natural world may be described in terms of underlying simple objects, concepts, and laws of behavior (mechanics) and interactions. When we look still closer we see that these simple objects are composite objects whose internal structure may be complex and have a wealth of possible behavior. Somehow, the wealth of behavior is not relevant at the larger scale. Similarly when we look at longer length scales than our senses normally are attuned to, we discover that the behavior at these length scales is not affected by objects and events that appear important to us.

Examples are found from the behavior of galaxies to elementary particles: Galaxies are composed of stars and interstellar gasses, stars are formed of complex plasmas and are orbited by planets, planets are formed from a diversity of materials and even life, materials and living organisms are formed of atoms, atoms are composed of nuclei and electrons, nuclei are composed of protons and neutrons (nucleons), and nucleons appear to be composed of quarks.

Each of these represents what we may call a level of description of the world. A level is an internally consistent picture of the behavior of interacting elements that are simple. When taken together, many such elements may or may not have a simple behavior, but the rules that give rise to their collective behavior are simple. We note that the interplay between levels is not always just a self-contained description of one level by the level immediately below. At times we have to look at more than one level in order to describe the behavior we are interested in.

The existence of these levels of description has led science to develop the notion of fundamental law and unified theories of matter and nature. Such theories are the self-consistent descriptions of the simple laws governing the behavior and interplay of the entities on a particular level. The laws at a particular level then give rise to the larger scale behavior.

The existence of simplicity in the description of underlying fundamental laws is not the only way that simplicity arises in science. The existence of multiple levels implies that simplicity can also be an emergent property. This means that the collective behavior of many elementary parts can behave simply on a much larger scale.

The study of complex systems focuses on understanding the relationship between simplicity and complexity. This requires both an understanding of the emergence of complex behavior from simple elements and laws, as well as the emergence of simplicity from simple or complex elements that allow a simple larger scale description to exist.

More technically, by considering systems as a function of scale we learn that macroscopic behavior of physical systems can be described or determined by only a few relevant parameters. These parameters arise from the underlying microscopic description. However, many of the aspects of the microscopic description are irrelevant. Different microscopic models can be used to describe the same macroscopic phenomenon. The use of multiscale methods of scaling and renormalization does not assume that all the details of the microscopic description

become irrelevant, however, they seek to determine which of the microscopic parameters are relevant to the macroscopic behavior in order to enable us to simplify our analysis and come to a better understanding.

Whenever we are describing a simple macroscopic behavior, it is natural that the number of microscopic parameters relevant to model this behavior must be small. This follows directly from the simplicity of the macroscopic behavior. On the other hand, if we describe a complex macroscopic behavior, the number of microscopic parameters that are relevant must be large.

Nevertheless, we know that the renormalization group approach has some validity even for complex systems. At long length scales, all of the details that occur on the smallest length scale are not relevant. The vibrations of an individual atom are not generally relevant to the behavior of a complex biological organism. Indeed, there is a pattern of levels of description in the structure of complex systems. For biological organisms, composed out of atoms, there are additional levels of description that are intermediate between atoms and the organism: molecules, cells, tissues, organs and systems. The existence of these levels implies that many of the details of the atomic behavior are not relevant at the macroscopic level.

This should also be understood from the perspective of multiscale modeling or analysis. When we are describing the behavior of a complex system, we have the possibility of describing it at a very coarse level or a finer and yet finer level. The number of levels that are necessary depends on the level of precision or level of detail we wish to achieve in our description. It is not always necessary to describe the behavior in terms of the finest scale. It is essential, however, to identify properly a model that can capture the essential underlying parameters in order to discuss the behavior of any system.

Like biological organisms, man-made constructs are also built from levels of structure. This method of organization is used to simplify the design and enable us to understand and work with our own creations. For example, we can consider the construction of a factory from machines and computers, machines constructed from individual moving parts, computers constructed from various components including computer chips, chips constructed from semiconductor devices, semiconductor devices composed out of regions of semiconductor and metal. Both biology and engineering face problems of design for function or purpose. They both make use of interacting building blocks to engineer desired behavior and therefore construct the complex out of the simple. The existence of these building blocks is related to the existence of levels of description for both natural and artificial systems.

Our discussion thus brings us to recognize the importance of studying the properties of substructure and its relationship to function in complex systems. This relationship is very general and is discussed for neural networks and cognition in Chapter 2 of *Dynamics of Complex Systems*.

\* Adapted from [Dynamics of Complex Systems Section 1.10.8](#).