Two most important concepts for understanding complex systems are emergence and self-organization.

Emergence lacks a clear and widely accepted definition, but it is generally understood as a property of a

system that is not predictable from the properties of individual system components. There is a continuum

of emergence spanning multiple scales of organization. Halley andWinkler argue that simple emergence

occurs in systems at or near thermodynamic equilibrium, whereas complex emergence occurs only in

nonlinear systems driven far from equilibrium by the input of matter or energy [153].

Physical phenomena that do not manifest themselves at microscopic scales but occur at macroscopic

scale are manifestations of emergence. For example, temperature is a manifestation of the microscopic

behavior of large ensembles of particles. For such systems at equilibrium, the temperature is proportional

with the average kinetic energy per degree of freedom. This is not true for ensembles of a small number

of particles. Even the laws of classical mechanics can be viewed as limiting cases of quantum mechanics

applied to large objects.

Emergence could be critical for complex systems such as financial systems, the air-traffic system, and

the power grid. The May 6, 2010, event in which the Dow Jones Industrial Average dropped 600 points

in a short period of time is a manifestation of emergence. The cause of this failure of the trading systems

was attributed to interactions of trading systems developed independently and owned by organizations

that work together, but their actions were motivated by self-interest.

A recent paper [329] points out that dynamic coalitions of software-intensive systems used for

financial activities pose serious challenges because there is no central authority and there are no means

to control the behavior of the individual trading systems. The failures of the power grid (for example,

the Northeastern U.S. blackout of 2003) can also be attributed to emergence; indeed, during the first few hours of this event, the cause of the failure could not be identified due to the large number of independent

systems involved. Only later was it established that multiple causes, including the deregulation of the

electricity market and the inadequacy of the transmission lines of the power grid, contributed to this

failure.

Informally, self-organization means synergetic activities of elements, when no single element acts

as a coordinator and the global patterns of behavior are distributed [137,320]. The intuitive meaning

of self-organization is captured by this observation of mathematician Alan Turing [355]: “Global order

can arise from local interactions.”

Self-organization is prevalent in nature; for example, in chemistry this process is responsible for

molecular self-assembly, for self-assembly of monolayers, for the formation of liquid and colloidal

crystals, and in many other instances. Spontaneous folding of proteins and other biomacromolecules,

the formation of lipid bilayer membranes, the flocking behavior of various species, the creation of

structures by social animals – all are manifestations of self-organization of biological systems.

Inspired by biological systems, self-organization was proposed for the organization of different types

of computing and communication systems [169,231], including sensor networks, space exploration

[167], or even economic systems [200].

The generic attributes of complex systems exhibiting self-organization are summarized in Table 10.1.

Nonlinearity of physical systems used to build computing and communication systems has countless

manifestations and consequences. For example, when the clock rate of a microprocessor doubles, the

power dissipation increases from 22 = 4 to 23 = 8 times, depending of the solid-state technology

used. This means that the heat-removal system of much faster microprocessors has to use a different

technology when we double the speed. This nonlinearity is ultimately the reason that in the last few

years we have seen the clock rate of general-purpose microprocessors increasing only slightly,3 while

the increased number of transistors postulated by Moore’s law, allow companies such as Intel and

AMD (Advanced Micro Devices) to build multicore chips. This example also illustrates the so-called

incommensurate scaling, another attribute of complex systems. Incommensurate scaling means that, when the size of the system or one of its important attributes such as speed increases, different system

components are subject to different scaling rules.

The fact that computing and communication systems operate far from equilibrium is clearly illustrated

by the traffic carried by the Internet. There are patterns of traffic specific to the time of the day, but

there is no steady-state. The many scales of the organization and the fact that there are different patterns

at different scales is also clear in the Internet, which is a collection of networks where, in turn, each

network is also a collection of smaller networks, each one with its own specific traffic patterns.

The concept of phase transition comes from thermodynamics and describes the transformation, often

discontinuous, of a system from one phase or state to another, as a result of a change in the environment.

Examples of phase transitions are freezing, which is a transition from liquid to solid, and its reverse,

melting; deposition, which is a transition from gas to solid, and its reverse, sublimation; and ionization,

which is a transition from gas to plasma, and its reverse, recombination.

Phase transitions can occur in computing and communication systems due to avalanche phenomena,

when the process designed to eliminate the cause of an undesirable behavior leads to a further deterioration

of the system state. A typical example is thrashing due to competition among several memory intensive

processes, which leads to excessive page faults. Another example is acute congestion, which

can cause a total collapse of a network; the routers start dropping packets and, unless congestion avoidance

and congestion control means are in place and operate effectively, the load increases as senders

retransmit packets and the congestion increases. To prevent such phenomena, some form of negative

feedback has to be built into the system.

A defining attribute of self-organization is scalability – the ability of the system to grow without

affecting its global function(s). Complex systems, encountered in nature or man-made, exhibit an

intriguing property: They enjoy a scale-free organization [39,40]. This property reflects one of the few

attributes of self-organization that can be precisely quantified. The scale-free organization can best be

explained in terms of the network model of the system, a random graph [53] with vertices representing

the entities and the links representing the relationships among them. In a scale-free organization, the

probability P(m) that a vertex interacts with m other vertices decays as a power law, P(m) ≈ m−γ ,

with γ a real number, regardless of the type and function of the system, the identity of its constituents,

and the relationships among them.

Empirical data available for social networks, power grids, theWeb, or the citation of scientific papers

confirm this trend. As an example of a social network, consider a collaborative graph of movie actors on

which links are present if two actors were ever cast in the same movie; in this case, γ ≈ 2.3. The power

grid of theWestern United States has some 5,000 vertices representing power-generating stations, and in

this case, γ ≈ 4. For theWorldWideWeb the exponent is γ ≈ 2.1; this means that the probability that m

pages point to one page is P(m) ≈ m−2.1 [40]. Recent studies indicate that γ ≈ 3 for the citation of scientific

papers. The larger the network, the closer a power law with γ ≈ 3 approximates the distribution [39].