Collective Behavior – A General Survey

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Abstract ***– Collective behavior is a form of action that is neither conforming (in which actors follow prevailing norms) nor deviant (in which actors violate those norms). It is a spontaneous manifestation of the ensemble and it results from the complex interaction mechanism between the actors. In societies usually it takes place when norms are absent or unclear, or when they contradict each other. Puzzling collective behavior can be observed in different societies including human social life and wildlife as well. It is also present in lifeless systems from physics, chemistry and engineering. Based on such well-known emerging behavior novel bio-inspired systems can be developed aimed for flexible manufacturing, systems control, traffic planning and several other advanced field of engineering. This paper deals with the theoretical background of the phenomena and offers a wide overlook of diverse forms of collective behavior in history, philosophy, psychology, sociology, biology, physics, chemistry and technology.***

***Keywords**: collective behavior, synchronization, cluster formation, trail formation, self-organization, phase transition.*

I. INTRODUCTION

The expression *collective behavior* – according to the British Encyclopedia – is a sociological term, and covers the types of activities engaged in by sizable, but loosely organized groups of people. Actions like riots, revolts, rebellions, revolutions, lynches, civil right or social reform movements, emergence of panic, disaster cycles, social epidemics, campus unrest, religious or nationalistic movements, terror, propaganda, emergence of fads, crazes, hearsay, gossip, rumor, memes, media hypes, or shifts of the public opinion can all be considered to be forms of collective behavior.

The 'collective behavior' expression was first used by Robert Park, as an alternative of crowd behavior [1]. He developed a theory about actions of groups. His theory was named later 'Collective Behavior' and became a trend of the Chicago sociological school. At the moment of its birth, collective behavior was only one of the theories designed to explain different aspects of contemporary society and the process of social change. In time the expression has become a collector concept that covers a large area of sociology, biology and physics, too.

II. COLLECTIVE BEHAVIOR IN HISTORY, PHILOSOPHY, PSYCHOLOGY AND SOCIOLOGY

Revolts, riots, rebellions occurred even in ancient times, but historians and philosophers considered them as irrational and destructive. Up to the 19th century philosophers and historians did not wonder too much about the behavior of mobs formed by poor, uncivilized people because they used to study the social network, organization, institutions and forces that guide man's behavior in a stable system.

This opinion changed slightly in the 19th century. The industrial revolution led to major changes not only in manufacturing, agriculture and mining, but also concerning social life. Riots, revolutions, counterrevolutions were on top all over Europe. Philosophers of this time could not just ignore the deep changes throughout the world and society, so they began to study these processes in order to know, predict, avoid or guide them. Their work gave birth to a group of social sciences dealing with different aspects of man's life in society. Sociology was born.

In the middle of the 19th century the French philosopher A. Comte recognized some aspects for the changes of the society and he formulated the need of making a distinct discipline to investigate and scientifically treat social statics and dynamics. His hope was that studying these would eventually help avoiding violent actions of masses.

A first serious study about the actions of a crowd was made by G. Le Bon. He recognized that the influence of masses will be continuously increasing. He also observed three main characteristics of crowds: *contagion* (ideas are spreading rapidly through a group, as a contagion), *anonymity* (the responsibility of individuals vanishes because the group confers them anonymity), and *collective mind* (individual responses, feelings, thoughts disappear, a crowd will form a single being). He realized that people act totally different when being in a group, as they would have acted individually, but he wanted to explain the behavior of a group based on the psychology of group members, and interactions among them. This idea is obsolete now: a sociologist of our times would let psychologists investigate the group members as individuals and he would deal with the group as a whole [2].

R. Park considered first the crowd as a reality, a socially constructed mechanism to override tradition. He accepted that circumstances do change, so the society has to adapt to this change. Furthermore he considered actions of crowds as a necessity, as a continuing process by which the new or modified order takes birth [2]. He developed his theory about actions of crowds, and used the expression 'collective behavior' as an alternative of crowd behavior. Park had a defining role in creating collective behavior as a separate field of study.

Blumer placed the collective behavior in a social context. He pointed out, that actions of groups are influenced by society itself [1], [2]. He defined collective behavior as being unpredictable actions of groups that emerge spontaneously, and disregard previous rules, traditions and understandings. Blumer realized that mass behavior has a growing magnitude and importance in the modern society. He pointed out that a mass of people forms and acts spontaneously just like a crowd does, but being made up of different, completely separated people, it cannot act with the unity that marks the crowd. He did not include mass behavior within the general category of collective behavior.

Collective behavior, in its classical meaning, covers actions of a group of people, facing the same, unusual situation and acting in a more or less unpredictable way, like a single human being. In this case, individuals interact strongly and directly with each other, especially with nearest neighbors, and they will produce typical crowd behavior such as riots, revolts, rebellions, lynches, campus unrest, emergence of a panic in case of fire or calamity.

N. Smelser [1] gave a slightly different definition of the 'collective behavior' term: he considered it an activity organized around some generalized belief and respondent to some stress-inducing situation. He included mass behavior within the category of collective behavior. This was a necessity, because the modern industrial world created new circumstances for the uprooted, alienated members of society. Primary groups have lost importance. The development of technology made possible the *mass production* and consumption and the revolution of communication gave birth to a new power: the *mass-media*.

In our days the wide-spreading of mobile phones, television, satellites, PCs and the outburst of Internet makes possible a rapid flow of information and brings new possibilities to connect people. *Networks* have always existed but in modern society, their number and importance have increased. The elements of a network connected to each other by modern means of communication, sharing at least one common issue, can form a virtual group despite of their physical separation.

Actions of a great number of anonymous individuals, isolated from each other, interacting indirectly, guided or manipulated by the mass-media, or interacting with each other, being part of a network (virtual group), can be considered collective behavior too. Examples for such actions are propaganda, emergence of fads, fashion, media hypes, social epidemics, or simple shifts of the public opinion.

In conclusion, collective behavior is performed by a great number of individuals facing one unusual common issue. The members are connected directly or indirectly. Collective behavior is a response to a given initial situation, and will have an effect on it and it will produce a feed-back on it, being in a continuous interaction with the social environment.

III. COLLECTIVE BEHAVIOR IN BIOLOGY

Biology offers a large number of examples for collective behavior: pattern formation, self-organization, trail formation, synchronization.

Many living creatures do form groups like swarms of bacteria, bees, or ants, flock of birds, fish-schools, herd of migrating ungulates. Man was curious about the behavior of animals, and observed it from the very beginning. Watching the bird flocks and fish schools, or the amazing life of termites, the first idea is to seek for similarities. At first glance some of these animals seem to live in their own "society" just like people do.

It's interesting to watch how ants work when finding some food supply which has bigger pieces than the ants themselves. They put their shoulder to carry it together. At first, this seems to be team-work, but it is not. All ants work hard, pulling the weight in an accidental direction, and this will move in the direction of the resultant force. Finally, they instinctively succeed to do something they couldn't do alone.

Migrating geese always respect their regulated V shape, making the impression of a highly organized group, having an experienced leader. Attentive observation will notice that the strong ones which tend to move with a bigger velocity will be in front, while the others will fly in the streamline created by those in front of them. In time members will change their positions: when the leader gets tired, it will slow down, so another one with bigger velocity will take its place.

Many species of fish do live in big groups. These huge fish-schools have in their frontlines the hungrier individuals. These are occasional leaders, too: after they have found food, they will choose to remain in the inner part of the group, being replaced by other hungry ones. This is – without any doubt – a well coordinated action. There were some early theories that tried to explain this behavior talking about a specific communicational ability of fish, but it has been proven, that the mechanism is much simpler, there isn't any supplementary communication. They simply see each other and individuals react very fast to the actions of their neighbors.

As some members observe an obstacle or a predator fish, they immediately turn. This sudden movement makes their neighbors turn and, in a very short time, makes the whole group turn. They react as a single living being. Flocks of birds or herds of ungulates can change direction in the same way. When being part of a herd, the actions of animals seem to be guided by more complicated processes, but this is not true. They do not have to have information about the whole system they are part of. Their movements are guided by simple rules: keeping an optimal distance from each other in order to avoid separation, but not to bump in each other. Seen from above our perception is that they move forward as a single entity having a wave-shaped herd-front line. Despite appearances, none of them is aware of being in a herd, nor about the size or shape of it.

Sometimes tiny insects perform really complex behavior: the society of bees seems to be highly organized: the working bees feed their successors, and protect them in case of danger. As shown above, this is not due to a highly organized order: it is simply the consequence of some genetically coded information.

Bees can transmit each other the distance, direction and quantity of the discovered food supplies. This is finally, something that really brings them closer to human beings: they do have, at least, some means of communication.

When ants find a food source, they seemingly announce each other about it, but the real mechanism of trail formation is much simpler. They mark these trails with pheromones, and as time passes, and more and more ants pass on the same way, this will be marked better and better, creating a positive feedback. This kind of repeated actions will lead to trail formation, and will produce changes in the environment.

All these phenomena are performed by systems made up of a big number of interacting entities. Their complex activity seems to be highly organized, although guided by very simple rules.

The system is able to interact continuously with its environment, changing it, and giving complex and unpredictable, quick responses to these changes. The result is a good adaptation of the group to the environmental changes.

These phenomena were labeled by biologists using simple, suggestive expressions, like *trail formation*, *pattern formation*, *synchronization* or *self -organization*.

IV. COLLECTIVE BEHAVIOR IN PHYSICS

Many-body problems, pattern formation in vibrated granular matter, emergence of fingering, vortices or avalanches, segregation, phase-transition, spontaneous magnetization, crystallization or synchronization phenomena can all be considered as examples for collective behavior. All these phenomena arise in systems formed by many interacting elements. The whole system behaves in a different manner than their components would. The elements all interact with their environments, producing finally effects on a larger scale, than an individual could: the "whole" in such cases is much more than a simple sum of the individuals.

Physics dealt with collective behavior much earlier than the expression collective behavior was even born! Systems with a big number of interacting components that together can produce effects on a larger scale is familiar to physicists, but most of these phenomena had a special name and model in physics.

Probably the earliest observed collective behavior was that of the Solar System. It was named the *celestial motion,* or later referred to as a *many-body problem*.

One of the first physicists who studied collective behavior through the specific phenomenon of *synchronization* was Huygens. He observed the correlated motion of pendulum clocks hung on the same wall and assumed correctly that the clocks synchronize, due to the interaction among them. In the 19^{th} century synchronization was described as a phenomenon which occurs in case of coupled oscillators. Appleton and Van der Pol made a theoretical and experimental study of the synchronization of triode generators and tried to describe the sync phenomenon using coupled electric circuits [3].

The phenomenon of *pattern formation* was first described by Chladni. He made experiments to improve the musical instruments (violins) he manufactured. His experiments investigated the oscillation of plates with different shapes covered with tiny particles of dust and recorded on drawings the obtained patterns. His work is considered to be the starting point of acoustics.

Most of the phenomena emerging in a *thermodynamic* system can be considered collective behavior. A thermodynamic system is made up of molecules. The components of a solid, liquid or gas are identical, or much alike, and their number is huge. The interactions between the molecules and interaction with external fields produce a special environment for every individual. Again, the system is more than simply the sum of its parts. A thermodynamic system will produce, without any doubt, collective behavior. For example, during crystallization the components will simply "organize themselves", creating specific order. The process will be guided by interaction forces and will be influenced by the environment. Although this phenomenon carries all of the features of collective behavior, it is not called so, and usually referred to as *phase transition*, or simply *crystallization*. This is because thermodynamics developed as a separate field of physics, much earlier than collective behavior theory.

Studying interacting systems with a huge number of particles forced physicists to elaborate statistical study methods that became a primary tool for investigating collective behavior in many other disciplines as well. It became clear that it is impossible to handle the dynamics of each particle separately even despite the presently achieved revolution in Information Technology. Gathering the data about every component and describing the evolution of every individual in part will cause overflow of data, and it won't bring any benefits. It become clear that it is a much easier approach to capture the collective phenomena through simple models and to study these models using the consecrated methods of statistical physics. Statistical physics has built up or borrowed from other disciplines many simple many-body models that are useful for describing a wide range of collective behavior. Physics also elaborated the proper statistical methods to study analytically or by computer simulations these models

V. MAIN FORMS OF COLLECTIVE BEHAVIOR

A. Synchronization

Synchronization is a basic property of systems exhibiting rhythmic dynamics. The first scientist who mentioned synchronization was Huygens, as it was already mentioned in Section IV. He correctly explained the "sympathy" of the clocks with an interaction between them, but the mathematical model for this system was made much later in the 19^{th} century.

Rayleigh described the synchronization of two organ-pipes with the same pitch when standing close to each other [4].

Physics created the model of a linear oscillator, studied the dynamics of coupled oscillators and discovered the phenomenon of resonance. It became clear, that every oscillating system has its own period, and perfect synchronization can be obtained easily only in the case of identical oscillators.

At the end of the 19^{th} century a new era has started for mankind: the era of electricity and mass-communication. Synchronization has become an important issue for power generators and broadcasting, too. Electrical engineers working on construction of electric network systems noticed that alternative current generators connected in parallel tend to synchronize [5]. But the most amazing discoveries were up to come only afterwards: The idea of energy quantification (and implicitly quantum physics) was born together with the 20^{th} century. The existence of quantum oscillators with quantized energies seemed incredible, but experiments and later applications scattered all doubts. It became clear, that the emission of laser light is a result of synchronization: a big number of excited atoms will synchronously fall on their ground state, each emitting a photon each of them. After discovering superconductivity, physicists realized, that coupled Josephson junctions will also synchronize as pendulums do.

It became quite accepted that similar models and equations can describe the behavior of coupled pendulums, of coupled electrical generators, or coupled Josephson junctions [3]. Both physicists and engineers were aware that there are several examples of *rhythmicity* and synchronization in other areas of science. In biology the synchronization of flashing fireflies or crickets chirping in unison, heartbeats, breathing or walking are only some examples. By exploring the rhythms of living organisms, rhythmical behavior of plants, animals or people, synchronization became an important issue of researchers.

J.J.D. de Mairan was the first scientist who experimented in such sense on sun-sensitive plants. He was interested whether they keep their rhythm when being in a completely dark room. He found already in early 1720, that the plants continued to "respond" to the Sun even if they were kept out of its sight. This experiment evidenced the existence of inner rhythms of plants. This rhythm was named later *circadian rhythm*. Similar observations and experiments were made on other animals and people, too. For example volunteers lived long periods in caves, lacking any information about external life, in order to offer precious information about the circadian rhythm of humans [3]. It was shown that every living organism has its own specific rhythm and in the same way, many organs do have their own inner rhythms too. In case of isolation this rhythms could slightly differ from the normal period imposed by the motion of Earth, but under normal conditions they are adapted to it. It was observed that some ant colonies synchronize their bouts of resting and activity. The pipistrel's heart beats 1000 times a minute, while the elephant's only 20 times. Neurons can transmit 1000 impulses per second, some beetle can move their wings with this frequency, but cilia of some unicellular organisms make only 2 to 40 movements per second [7].

Humans' sleeping mode switches every 80-90 minutes, the average menstrual cycle of women is 28 days, but propagation of different animal species can have annual or even longer rhythms [7]. It was also observed that women's menstrual cycle synchronizes in the case of living or working close together.

It was noticed long ago that certain firefly species were blinking in synchrony on summer evenings [6]. The male fireflies will adjust their flashing to each other in order to emit light simultaneously. The number of flashes per second was recorded and studied. It became clear that these bugs can adjust their phase and they emit light in synchrony. The number of flashes can vary from one to five flashes per second, depending on the species.

The emergence of rhythmic applause in European concert halls was studied, too. After a performance, the applause can develop in two alternating ways: an unsynchronized one, having a higher intensity of sound, and a synchronized one, with a constantly rising rhythm and intensity of sound. The rhythm will grow till synchronization breaks, and the applause returns to an unsynchronized mode [8]. It was shown, that sync occurs in case of pedestrian walk. When people walk together, they tend to synchronize their steps. This variety of examples makes to understand that synchronization is an intrinsic property of nature.

Sync is a collective behavior that emerges in any system that has many tiny oscillating components, weakly coupled to each other. Regardless the initial condition, the system will synchronize, this sync state being a very stable one: once sync emerges, the system will remain sync, and small perturbations will not change this situation.

Synchronization phenomena of coupled mechanical or electrical oscillators (pendulums, electric circuits, triode generators quantum oscillators), rhythmic activities of living organisms bounded to celestial motion, breath-taking or walking can all be modeled with *coupled oscillators* [9]. The model of frequency-coupled, phase-coupled classical or stochastic oscillators could describe with success a large amount of specific synchronization phenomena among biological or chemical oscillators (neurons communicating via electric spikes, synchronized fireflies-flashing or crickets-chirping).

B. Self-organization and pattern formation

Patterns can be met almost all over our world and they are part of our every-day life. In art we will call it a recurring motif, and in everyday life we record it as a strange form. A sequence of numbers generated according to a certain law gives a mathematical pattern. In computer science a design pattern is a general solution to a problem. Nowadays, pattern formation means the strange and puzzling forms occurring as a result of some collective behavior.

Actually, most self-organizational phenomena have as a result the emergence of some sort of pattern. First of all, this means a spatial order, but sometimes it can mean the alternation of different patterns in time.

Both self-organization and pattern forming imply a big number of elements. Scientists working in different fields gave different names to the collective phenomena they came across, but, recognizing the similarities among them, they used them alternatively. This is why it is almost impossible to separate self-organization from pattern formation.

It was mentioned earlier that *pattern formation* phenomenon was first observed in the 18^{th} century by Chladni, by bringing in oscillation membranes of different shapes covered with a thin granular layer. The emerging patterns he observed were of different shapes, depending not only on frequency and amplitude, but also on the size of particles or pressure of ambient gas too [10]. In the case of vertically vibrated fluids rectangular, striped, hexagonal and even transient spiral pattern can be obtained. The symmetry of these patterns depends on the frequency of vibration, viscosity and depth of the fluid layer [11].

Pattern formation is present in etiology, biology or sociology: in the V-shape of migrating geese or the different shape or spatial arrangement in the herds of group-living vertebrates or fish-schools, in the nests made by social insects, in swarms of bacteria, in biological systems or patterns of traffic flow in human crowds [12], [13], [14].

The coats of mammals do have specific design [15], [16]. These are patterns produced by bio-chemical reactions and have an important role in the evolution of species. Patterns also occur on seashells, in the trunk of trees, special distribution of sea-algae on the bottom of the sea. Seen from above, a crowd can form different patterns, it may look like a wave or a whirlpool. In fact every process of fetal development, or crystal growth implies pattern formation [16].

A process is considered pattern formation if is a result of simple rules or simple interactions. Usually a complex order emerges in the system, ending up in a puzzling spatial-temporal arrangement. This happens due to the interactions among the individual components of the system [12].

According to a definition given by Tsmirning, "pattern formation is a dynamical process leading to the spontaneous emergence of a nontrivial spatially non-uniform structure which is weakly dependent on initial and boundary conditions" [10].

This definition refers to spatial patterns, but it can be extended to the case when different spatial-temporal arrangements come one after the other, like in the case of oscillating chemical reactions (known examples are the Belousov-Zhabotinsky or Briggs-Rauscher reaction) [17], [18]. Other examples are when axial segregation patterns can have oscillatory behavior or traveling waves could emerge in long rotated drums (for example in case of binary mixtures of granular material) [10], [19].

C. Cluster formation

At first sight *clusters* are also patterns, a collection of elements in groups with diverse sizes. The elements of the group are linked together by much stronger interactions than its links to the rest of the population. A group formed in such manner will be called a cluster. One can speak about clusters of atoms, formed by only a few or by a very big number of components. Probably, the most known example is the buckminsterfullerene, a cluster of 60 carbon atoms having the form of a football.

Another example for clusters comes from art. Wet paint will get dry gradually, and, as water evaporates, the remaining particles would cling together forming the tiny paint-isles seen on the canvases of the famous painters. Similar phenomenon occurs in the drying mud, or the sunburn land. The most spectacular clusters are those formed by the stars of a galaxy.

The most interesting example of cluster formation in the context of collective behavior is the appearance of cliques or coalitions in a group of actors (people, countries, companies) with a complex relation among them.

D. Trail formation

Trail formation is not only specific for ants, but for many other animals, or even for human beings. When moving through a big snow-covered area, a rough, bumpy ground, or a plain covered with grass, people will prefer to follow previously used ground. This kind of repeated actions will lead to trail formation, and will produce changes in the environment.

In case of intense traffic, when there are many people along a walkway moving in both directions, pedestrians having the same direction will form bands too.

Trail formation has some mechanisms that make this type of collective behavior a separate one. The environment has a big influence on this process, but weak interactions among participants are present, too (indirect interactions, positive and negative feedback).

Trail formation could be linked to pattern formation or self-organization as well. As a result of trail formation a pattern arises, and the multitude of trails forms networks as in the case of naked malls. The process of trail formation is a self-organization phenomenon too, because of the indirect interactions among participants. Some authors labeled this type of systems as being CAS (*Complex Adaptive Systems*). This suggests that the system formed by many interacting components evolves with the environment. As the result of the multiple interactions with neighbors and the environment, the system continuously changes, creating new circumstances for his own (the herd of ungulates, as well as trails, paths made by human beings will change the landscape).

Trail formation is a good example of collective behavior, where the processes may be explained without invoking any intellectual contribution of the individuals. This process can be modeled as movement of a number of mass points, under the influence of some simple interaction forces.

The motion of a big number of interacting mass points can perform realistic collective behavior if the repulsion and attraction forces among them are properly chosen. Simple physical models can be used to describe the dynamics of ungulate herds, bird flocks and fish-schools, but in many cases group dynamics in puzzling social phenomena too (like the spreading of rumors, fads, crazes or opinion shifts.) Despite the difference in the complexity of social groups and simplicity of particles dynamics governed by physical forces, both of them can be described by common models [12]. This approach is applicable to activities of humans in the case when the interaction among them is reduced to a very simple one, for example the motion of pedestrians within crowds, or panic situations [12].

E. Self-organization

In many cases the pattern formation phenomena is referred as *self-organization*. Camazine [20] defines self-organization as "a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of a system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern [20]. Both the pattern formation and self-organization can be defined as a phenomenon produced by a system having a big number of components. These components interact with each other and the environment. In the case of pattern formation, the components of the system are influenced mainly by the environmental changes and are influenced by initial conditions. Self-organized systems are often guided by the emerging positive or negative feed-back loops. The components do interact with each other and with the environment too. They produce their effects on the environment and on their neighbors, too.

It is hard to make a clear difference between self-organization and pattern formation: some authors considered self-organization a collector concept for pattern formation in biological systems, vertebrate groupings, trail formation, and the generation and use of collective trail systems as well [12]. Others talked about "self-organized patterns", and some used only one of the expressions [21], [22]. Based on their work, an attempt can be made to give separate definitions for the two expressions.

When the order emerges as a result of the interactions among the participants, and external factors do not have a big influence on the process, this can be considered self-organization. In the case of social systems, a team that does not act under the command of an authority is self-organized. While neither the fish-schools nor the ungulate herds follow a leader, they can be labeled as self-organized. It seems that in case of vibrated layers this expression is not suitable, because there are some external stimuli which have the main role in the emergence of the pattern.

Although avalanche-forming is guided by gravity forces and the self-organization is not suitable for this process, P. Bak introduced the expression self-organized criticality quite referring to the behavior of avalanches formed in sandpiles [23]. He used this expression to suggest the possibility of replicating or sudden growing. The heaps of granular matter all have a specific angle of repos. At first approximation, if the angle is equal to this value, a small grain which falls will kick off many particles, so avalanche forming has a big probability. In order to model the behavior of sandpiles, P. Bak used the mathematical model called *cellular automaton* [24].

The idea of cellular automata comes from biology, where the living cells do have the ability of replicating themselves (these systems usually have some possibilities to "heal" the process, if a small disturbance occurred). Some mathematical patterns do have similar proprieties: they arrive to "stability" after a number of steps.

As the crystallization is guided by simple interactions and influenced by the environment, a regeneration process or fetal development has to be guided by simple interactions too. As a result of this, a new complex system emerges, made up of tiny entities, which do have the possibility to replicate themselves. This seems very familiar in biology, but might look strange in physics. Realizing a non-living entity or a machine that can replicate itself seems utopia for physics.

In fact the first cellular automaton was a mathematical exercise realized by the mathematician J. von Neumann, who made up a set of simple rules, which would have as a result the endless replication of itself [25]. This is the way fractals were also generated. One of the specific features of fractals is the scale invariance: on large scale, their symmetry is the same as on small scale. Many living or non-living organisms can have these properties: shapes of trees, the inner and the visible structure of leaves or plants.

F. Phenomena leading to scale-free distributions

Sometimes collective phenomena lead to scale-free power law distributions. The first who noticed this interesting distribution was the Italian economist and sociologist Wilfredo Pareto [26]. He figured out that in capitalist economics, the number of individuals having a greater wealth or income than a given value will decrease according to a power law.

This simple rule proved to be quite a general one characteristic not only for different economies, but for many other fields as well. The very same type of distribution governs the energy released in an earthquake, visitors of different websites, size of cities, frequency of words in a text or species in a territory.

The mentioned examples are all distributions obtained in systems having a big number of components; these components interact with each other and as a result of this interaction universal distribution patterns arise. Briefly we can conclude that, scale-free power-law distribution shows the presence of collective behavior. Such kind of distribution is always a hint of the system's complexity.

G. Phase transition

Phase transition is an expression which has its origins in physics and chemistry. First of all, it labels a process when a substance changes from one state (solid, liquid, gaseous) to another. This process takes place with a change of the structure of matter. In such sense we speak about phase transition when – for instance – water freezes. There is a wide variety of examples for such structural phase transition: transition among different molecular structures, different crystal structures (allotropes), or between a crystal structure and an amorphous one. Non structural phase-transition is the emergence of superconductivity in case of a metal cooled below a critical temperature or the transition which occurs in magnetic materials at Curie temperature, when they turn from ferromagnets to paramagnets [27]. Phase transition has thus a general meaning too: it covers all phenomena which implies sudden changes of characteristics when it is close to a critical state.

Phase transition is connected to almost every phenomena of collective behavior. There can be phase transitions fro example among different modes of synchronization or between the synchronized or unsynchronized state of a system. Phase transition can be also mentioned also in the context of the appearance of spatial ordering or patterns.

Such a "leap" characteristic to phase transition, occurring at a critical point can separate the two states of a biological or sociological system. For example when the number of ants or bees in a swarm reaches a critical number, they are split into separate swarms; if the number of individuals does not get to a certain limit, they would not produce collective behavior; for the emergence of panic it is necessary to have a certain number of people in the same mood [28].

IV. CONCLUSIONS

Any trial to make an accurate and clear classification of collective behavior fails. This has probably more causes: we deal here with a huge number of different phenomena. These may have some mutual characteristics or mechanisms, but they also differ in many details. Making a model means a simplification, the description of only some aspects of the phenomena. Different types of collective phenomena are different models appropriate for describing different aspects and this is why in many cases the same phenomena can be considered as belonging to several types of collective phenomena. This makes it also clear, why all attempts made for finding a unified description of collective behavior phenomenon failed.

We have to be content with some general rules and models that can be used to describe a bunch of phenomena which resemble in some aspects. The point is to search simple universal models, to fit the existing models to the concrete cases, or, if necessary, search for models which would describe the reality better.

When investigating collective behavior, focusing only on the behavior of one single component of the system is not helpful. By trying to make a complete analysis of each element, setting up the rules for these taking the system into parts and then putting it together is not a viable way. In such an approach the essence would be lost since the system cannot be perceived as a simple sum of its parts; it is much more than this. It is true that the system is made up of individuals, but the essence lies not in the elements but rather in their interaction and in their interaction with the environment. This is true for biological and social systems too. It is useless and frequently impossible to describe the behavior of every individual in part, when the final score is to describe the system. One element's behavior is usually not significant for the whole group. In social systems for example it has no sense to make a psychological investigation of the members, when our final scope is to investigate the system. This observation is also true for animal groups: shooting down fro example the leader of migrating geese will disturb for a moment the regulated V shape of the birds, but soon another one will take his place. The journey is over for the individual but continues for the rest of the ensemble. The flock will still remain stable.

In conclusion, in order to investigate collective behavior the whole system has to be targeted right from the beginning. Statistical physics constructed for this probably the simplest, so the easiest-to-use models. It also elaborated many specific experimental and theoretical study methods. This is why physicist has nowadays an important word to say in studies investigating sociological, ethological or even biological processes. Many disciplines benefited by the models of physics. When it comes however to explain results and make the accurate mathematical description of the gathered information, mathematics and informatics has a decisive role. The study of collective behavior is a truly inter- and multidisciplinary challenge. It is possible to study such phenomena only by putting together the results and research methods of different fields of sciences.

REFERENCES

[1] N.J. Smelser and N. Joseph, *Theory of collective behavior*. London (UK): Routledge & Kegan Paul, 1962.

[2] L.C. Warren, "*Two views of dissolution: an examination of collective behavior theory and critical theory on the subject of mass social behavior*," Simon Fraser University, 1976.

[3] S.H. Strogatz, *Sync: The emerging science of spontaneous order*: Hyperion, 2003.

[4] M. Rosenblum and A. Pikovsky, "Synchronization: from pendulum clocks to chaotic lasers and chemical oscillators," *Contemporary Physics,* vol. 44, pp. 401-416, 2003.

[5] I. Boldea, *Variable speed generators*: CRC Press, 2006.

[6] J.F. Case and F.E. Hanson, "The luminous world of John and Elisabeth Buck," *Integrative and Comparative Biology,* vol. 44, p. 197, 2004.

[7] C. Rocşoreanu*, et al.*, *The FitzHugh-Nagumo model: bifurcation and dynamics*: Springer Netherlands, 2000.

[8] Z. Néda*, et al.*, "Synchronization of two-mode stochastic oscillators: a new model for rhythmic applause and much more," *Physica A: Statistical Mechanics and its Applications,* vol. 321, pp. 238-247, 2003.

[9] A. Nikitin*, et al.*, "Collective dynamics of two-mode stochastic oscillators," *Physical Review Letters,* vol. 87, p. 24-101, 2001.

[10] I.S. Aranson and L.S. Tsimring, "Patterns and collective behavior in granular media: Theoretical concepts," *Reviews of modern physics,* vol. 78, p. 641, 2006.

[11] D. Binks*, et al.*, "Effect of depth on the pattern formation of Faraday waves," *Physical Review Letters,* vol. 79, pp. 5010-5013, 1997.

[12] I.D. Couzin and J. Krause, "Self-organization and collective behavior in vertebrates," *Advances in the Study of Behavior,* vol. 32, pp. 1-75, 2003.

[13] E. Bonabeau and G. Theraulaz, "Swarm smarts (behavior of social insects as model for complex systems)," *Scientific American,* vol. 282, pp. 72-74, 2000.

[14] E. Ben-Jacob and H. Levine, "Self-engineering capabilities of bacteria," *Journal of The Royal Society Interface,* vol. 3, p. 197, 2006.

[15] S. Camazine, "Patterns in nature," *Natural history. New York NY,* vol. 112, pp. 34-41, 2003.

[16] N. Suzuki*, et al.*, "Traveling stripes on the skin of a mutant mouse," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 100, p. 9680, 2003.

[17] R. Yoshida, "Self Oscillating Gels Driven by the Belousov-Zhabotinsky Reaction as Novel Smart Materials," *Advanced Materials,* vol. 22, pp. 3463-3483, 2010.

[18] G. Szabó*, et al.*, "Periodic CO and CO_2 evolution in the oscillatory Briggs-Rauscher reaction," *The Journal of Physical Chemistry A,* vol. 111, pp. 610-612, 2007.

[19] Y. Forterre and O. Pouliquen, "Long-surface-wave instability in dense granular flows," *Journal of Fluid Mechanics,* vol. 486, pp. 21-50, 2003.

[20] S. Camazine, *Self-organization in biological systems*: Princeton University Press, 2001.

[21] D.E. Juanico*, et al.*, "Self-organized critical branching in systems that violate conservation laws," *New Journal of Physics,* vol. 9, p. 92, 2007.

[22] I. Prigogine*, et al.*, "Order out of chaos." vol. 1, ed, 1984.

[23] P. Bak, *How nature works: the science of self-organized criticality* vol. 212: Copernicus New York:, 1996.

[24] Z. Olami*, et al.*, "Self-organized criticality in a continuous, nonconservative cellular automaton modeling earthquakes," *Physical Review Letters,* vol. 68, pp. 1244-1247, 1992.

[25] K. Preston and M.J.B. Duff, *Modern cellular automata: theory and applications*: Springer, 1984.

[26] B.C. Arnold, *Pareto distribution*: Wiley Online Library, 1983.

[27] A.H. Morrish, *The physical principles of magnetism*: Wiley New York, 1965.

[28] D. Helbing*, et al.*, "Simulating dynamical features of escape panic," *Nature,* vol. 407, pp. 487-490, 2000.