

# COLLECTIVE BEHAVIOUR OF PEOPLE

*An essay on the applications of statistical physics to humans*

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## 1. Introduction

There has been a recent boost in the application of ideas/methods/result of statistical physics to a wide range of phenomena occurring outside of the realm of the non-living world. Examples include models developed for biological macromolecules, bacteria colonies and, among others, for the various group activities of people. Here, in the form of an essay, we shall give a somewhat subjective account of the potential applications, involving the interpretation of such human activities as group motion, network formation and synchronization.

If you search for a collective behaviour related item with your web browser most of the texts popping up will be concerned with group activities of humans including riots, fashion or panics [1]. However, you will also find that on the other side of the complexity/size spectrum, in the world of atoms and molecules collective behaviour is also considered to be an important aspect of the observed phenomena. Furthermore, there are articles on collectively migrating bacteria, insects or birds and additional interesting results are published on collective phenomena in which groups of various organisms or non-living objects synchronize their signals or motion (e.g., fireflies flash in unison and people clap in phase during rhythmic applause).

What is common in these seemingly diverse phenomena involving interpretations ranging from social psychology to statistical physics? The answer is that they happen in systems consisting of many similar units interacting in a relatively well defined manner. These interactions can be simple (attraction/repulsion) or more complex (combinations of simple interactions) and may take place between neighbours in space or on a specific underlying network. Under some conditions, in

such systems various kinds of transitions occur; during these transitions the objects (particles, organisms or even robots) adopt a pattern of behaviour which is nearly completely determined by the collective effects due to the presence of all of the other objects in the system. Thus, the main features of collective behaviour are: i) the way an individual unit acts is dominated by the influence of its neighbours (the unit behaves differently from the way it would behave on its own) ii) such systems exhibit interesting ordering phenomena as the units simultaneously change their behaviour to a common pattern.

Ferromagnets are a good example. These materials can undergo spontaneous magnetization, in effect because they are made up of a host of "tiny magnets". At relatively high temperatures, these magnets cannot align with each other and the resulting magnetization is zero. But at a critical temperature the tendency to adopt a common direction suddenly, but continuously takes over from the effects of fluctuations. So most of the small magnets, assisting each other in a collective manner, point in the same direction, and magnetization (order) spontaneously appears. Similarly, a group of feeding pigeons randomly oriented on the ground will order themselves into a uniform flock while flying away after a big disturbance.

Perhaps the most important point I would like to make is that the concept of collective behaviour can be extremely useful due to its applicability to a wide class of processes in nature, including the group behaviour of people. In a way understanding a new phenomenon is usually realized by relating it to a known one; a more complex system is understood through analyzing its simpler variants. In the seventies there was a major breakthrough in statistical physics when a deep theoretical understanding of a general type of phase transitions was achieved due to the invention of the so called renormalization group method. This theory showed that the main features of transitions are insensitive to the details of the interaction between the objects in a system, thus, as an extreme case, orientational forces between atoms may result in ordering phenomena similar to those observed in groups of much more complex units.

Consider, as a thought experiment, thousands of people standing on a square and trying to look in the same – however, not previously determined – direction, after being asked to do so. A nice example for human collective behaviour would be if all of them managed to face the same direction. Can they do it? Statistical physicists can predict for sure that this cannot be done. They recall a theorem valid for particles with short ranged ferromagnetic interactions stating that in two dimensions no long range ordered phase (all magnets pointing in the same direction) can exist in such a system for any finite temperature and zero external field. So what happens? Locally people are looking almost in the same direction, but on a large scale, e.g., seen from a helicopter – just as the little magnets – they locally form vortex-like directional patterns due to the small perturbations due to human errors. Curiously enough, if the crowd is allowed to choose from a few discrete directions, the ordering can be realized. Perhaps even more interestingly, another

recent theory predicts that if the people are asked to move in the same direction they will be able to do it (just like the above mentioned flock of birds).

The interpretation of collective human behavior represents a great challenge for social sciences. In the following we discuss a new approaches to this problem based on the exact methods of statistical physics. We demonstrate that in cases when the interactions between the members of a group are relatively well defined (e.g, pedestrian traffic, segregation, rhythmic applause, panic, etc) the corresponding numerical models reproduce relevant aspects of the observed phenomena. Simulating models in a computer has the following advantages: i) by changing the parameters different situations can easily be created ii) the results of an intervention can be prognosed and iii) more efficient design of the conditions for the optimal outcome can be assisted. In addition to possible applications, our approach is useful in providing a deeper insight into the details of the mechanisms determining collective phenomena occurring in social groups.

Most of the results I am discussing below are available through the home page given in Ref. [1].

## 2. Motivation

Mankind has been experiencing a long successful period of technological development. This era has been the result of a deeper understanding of the various physical and chemical processes due to the outstanding advances in the related sciences. After these achievements there is now a growing interest in a better, more exact understanding of the mechanisms underlying the main processes in societies as well. There is a clear need for the kind of firm, reliable results produced by natural sciences in the context of the studies of human behavior. The revolution in information and transportation technology brings together larger and larger masses of people (either physically or through electronic communication). New kinds of communities are formed, including, among many others, such examples as internet chat groups or huge crowds showing up at various performances, transportation terminals or demonstrations. Since they represent relatively simple examples, these groups or communities of people provide a good subject from the point of studying the mechanisms determining the phenomena taking place in societies.

The behavior of masses of people is largely interpreted/influenced by politicians. Due to the revolution in information technology there is an increased potential for influencing the behavior of people on a large scale. Sophisticated technologies of mass manipulation have been worked out. Manipulation of people is generally looked at with a great amount of suspicion, although it is clear that it may lead to both bad and good results. On one hand, these developments have led to a certain mistrust in the theories/opinions presented by leading social scientists or politicians about social phenomena. On the other hand, the fact that masses of

people can be manipulated has increased both the expectations and the sensitivity concerning the related methods.

In short, there is a growing consensus that in several areas the present status of methods used for the description of human behavior should be surpassed. A possible direction is to make the approaches more quantitative so that the elements of subjectivity in the interpretation of the observed phenomena could be minimized. However, it is very difficult to study mass behavior by doing experiments which are traditionally looked at as the main source of fundamental, reliable information about any kind of phenomena. An experiment on collective human behavior would involve the repeated observation of hundreds or thousands of people under well controlled conditions; a situation which is hardly feasible without extreme efforts.

It is clear that the methods developed in natural sciences contain a significantly smaller amount of subjectivity than those used for the interpretation of human behavior. In the case these more exact approaches could be applied to social situations they could provide the desired objectivity, reproducibility and predictability. Since we are considering the behavior of a (large) group of people, it is natural to think of statistical physics as a potentially useful branch of sciences. The approach presented here is very recent. In addition to our efforts over the past few years summarised in part in Ref. [3], a few other groups have taken a similar direction, including a small firm in London [8] carrying out human crowd simulations for the police and a sociology faculty and his students in Gröningen who are developing computer programs for investigating the behavior of a mob during riots [9].

### **3. The science of many interacting similar units**

Statistical physics is a science of many interacting, simple and similar objects. In this context simple means that it is the interaction between the objects which matters from the point of the behavior of the system as a whole (the processes inside a single object can be neglected when the behavior of the entire system is considered). This interaction is relatively well defined (between each pairs of the objects) and is not too complex. The term particle is typically used for such objects. Over the last two and a half decades there has been a breakthrough in statistical physics and the concept that the collective behavior of many similar objects has a number of universal features has been established. Universal feature means that the details of the interaction do not change the character of the feature.

These phenomena can be very efficiently studied by the methods developed by statistical physicists. The related theoretical and numerical approaches provide reliable, sometimes exact description of the processes taking place in many particle systems.

Our important point is, that under some conditions a large group of humans can be considered as a collection of particles, since there are various situations

where the interaction of people is reasonably well defined (e.g., two people heading towards each other in a corridor will avoid each other just as if they had a repulsive physical force acting between them).

The methods of statistical physics include various approaches to the representation of a complex system. For the last two decades perhaps the most fruitful approach has been the application of *computer simulations*. In such studies a simple model is constructed which is supposed to grab the most relevant features of the system to be studied. Then, by letting the algorithm run in the computer while monitoring the parameters of the models a great variety of collective phenomena can be observed. The true test of a model is a careful comparison of its predictions with the behavior of the real system.

#### 4. Examples (Case Studies)

After these general introductory remarks, let us consider a few specific examples displaying most of the above mentioned features. It is hoped that the process of simultaneous investigation of particular examples and the abstraction of their most general features will lead to a coherent theoretical description of collective human behavior.

##### 4.1 COLLECTIVE MOTION

Here we first address the more general question whether there are some global, perhaps universal features of collective motion (typical changes in the pattern of motion) [3]. Such behavior takes place when many organisms are simultaneously moving and parameters like the level of perturbations or the mean distance between the individuals is changed.

A) *One-dimensional case*. Let us first consider a simple case of the particles (people) moving along a line (very narrow corridor, so that two people cannot get around each other). The particles are trying to maintain the same speed except when they are forced to turn back. There are only two rules: a) Follow the others, or in other words, try to take on the average velocity of your neighbors (who all move left or right). b) In addition, an amount of randomness is added to the actual velocity (to account for example for the level of excitement of the pedestrians).

Simulations result in a completely disordered motion if the level of perturbations is large (each particle moves back and forth randomly). However, if the noise is less, groups of particles are spontaneously formed, the groups merge (aggregate) and sooner or later join into a single large group moving in a direction determined in a non-trivial way by the initial conditions.

B) *Two dimensions*. Here the particles can get around each other and the pattern of motion is changed. Nevertheless, using the rules of "follow the others"

and the application of perturbations leads to a transition from a disorderly moving crowd to an ordered "flock" when the level of perturbations is lowered.

If the moving particles are subject to the "follow the others" rule, and they are confined to move around in a closed circular area than stable motion can be maintained only by the simultaneous rotation of all of the objects around the center. Interestingly enough, under some conditions even humans move in groups in a manner predicted by simple models. Indeed, in Mecca each year thousands of people circle around the Kaba stone as they are trying to both keep on moving and not confronting with others.

C) Next we focus on a system of *oppositely moving pedestrians* in a corridor. Here the corridor is wide enough (its width is several times larger than the diameter of a person). Half of the pedestrians is assumed to move from left to right, the rest in the opposite direction. In the associated model it is assumed that the particles tend to take on a constant speed in their desired direction and are avoiding each other due to a repulsive force.

Simulations of this simple model reproduce the experimentally observed behavior surprisingly well. A spontaneous formation of lanes of uniform walking directions in crowds of oppositely moving particles can be observed. It is clear that lane formation will maximize the average velocity in the desired walking direction which is a measure of the "efficiency" or "success" of motion. Note, however, that lane formation is not a trivial effect of this model, but eventually arises only due to the smaller relative velocity and interaction rate that pedestrians with the same walking direction have. In more detail, the mechanism of lane formation can be understood as follows: Pedestrians moving in a mixed crowd or moving against the stream will have frequent and strong interactions. In each interaction, the encountering pedestrians move a little aside in order to pass each other. This sideways movement tends to separate oppositely moving pedestrians. Moreover, once the pedestrians move in uniform lanes, they will have very rare and weak interactions. Hence, the tendency to break up existing lanes is negligible. Furthermore, the most stable configuration corresponds to a state with a minimal interaction rate [6]. Therefore, lane formation and minimal interaction rate are two sides of the same medal.

## 4.2 RHYTHMIC APPLAUSE

An audience expresses appreciation for a good performance by the strength and nature of its applause. The initial thunder often turns into synchronized clapping – an event familiar to many who frequent concert halls. Synchronized clapping has a well defined scenario: the initial strong incoherent clapping is followed by a relatively sudden synchronization process, after which everybody claps simultaneously and periodically. This synchronization can disappear and reappear several times during the applause. The phenomenon is a delightful expression of social self-

organization, that provides a human scale example of the synchronization processes observed in numerous systems in nature.

The above scenario can be recorded and the recordings analyzed using the techniques common in physics [4]. The analysis reveals various interesting features including a spontaneous period doubling (as compared to the natural period of a single spectator) when the synchronization takes place. In other words, after an initial asynchronous phase, characterized by high frequency clapping (Mode I), the individuals synchronize by eliminating every second beat, suddenly shifting to a clapping mode with double period (Mode II) where the dispersion (the relative difference in the clapping frequencies) is smaller. Statistical theories developed for a group of globally coupled periodically behaving objects can be used to demonstrate that the necessary condition for synchronization is that dispersion has to be smaller than a critical value. Consequently, period doubling emerges as a condition of synchronization, since it leads to slower clapping modes during which significantly smaller dispersion can be maintained. Thus, the evaluation of the measurements offer a key insight into the mechanism of synchronized clapping: fast clapping synchronization is not possible due to the large dispersion in the clapping frequencies. After period doubling, as Mode II clapping with small dispersion appears, synchronization can be and is achieved. However, as the audience gradually decreases the period to enhance the average noise intensity, it gradually slips back to the fast clapping mode with larger dispersion, destroying synchronization.

### 4.3 PANIC AND HERDING

Panic is a well known prototype of collective human behavior. Due to easier transportation and growing population people tend to turn up in very large numbers at various events. In addition to physical presence, people are brought together by other means as well. Because of the extremely fast ways by which information can be spread these days, a large group of people can learn about some undesired development forming a typical case for panic-like situation (bank panic is an example). Studies in social psychology have established a number of specific features of human behavior during panic. These investigations have mostly been concerned with the particular changes in the psychological state of a person in the related extreme circumstances. However, in order to be able to predict the definite outcome of the collective behavior of people involved we have to go beyond the traditional description and try to calculate the eventual time dependence of the behavior of the crowd as a whole. Here we discuss such an approach [5].

One of the most studied situation is when people in a closed area (room, department store, cinema) are considered after a sudden, alarming information (e.g., fire alarm goes on). These conditions can be well investigated by using computer models. The model we present is closely related to those described under Example 1. The situation which is to be interpreted by the model corresponds to a dark

(smoky) room, so that the escape route is not known *a priori*.

The particles representing people are randomly placed in a room shaped area which has one door where the particles can get out. The initial direction of motion is chosen randomly for each particle. The motion of the individual particles is determined by the following factors:

- Each particle is trying to maintain a well defined speed  $v_0$ .
- The direction of motion is determined by i) the direction of motion of the neighbors ii) a "panic parameter"  $p$ , iii) by a random perturbation and iv) by the presence of the wall of the room.
- If the panic parameter  $p$  is small, the particles tend to maintain their original direction. If  $p$  is large, they tend to give up their self-control and directly follow the average direction of their neighbors. For intermediate values the particles chose an intermediate direction; they both follow others and proceed in their original direction to a degree depending on  $p$ .
- The direction calculated as above is corrected by adding some amount of randomness which is characteristic for human decisions.
- If a particle arrives at a wall it adjusts its direction (is "reflected")
- At the "door" (absence of wall) the particles leave the room.

The simulations of the above model resulted in a surprising conclusion: a) For small panic it took a relatively long time for the room to become empty. The particles do not interact; they are trying to maintain the original direction (which, in general does not point directly towards the invisible exit) and finally escape only due to the accumulated effect of the applied random changes of direction. b) For large panic it also takes a long time to escape. The particles strictly follow each other and if the direction of a group of particles is not the right one, the system ends up in particles being stuck in one of the corners. c) For intermediate values, however, the particles escape from the room faster. In this case they have the tendency to follow others, but also change their direction due to other effects (randomness, wall) and turn away from a group which may head in a wrong direction. In this way they can join a group of particles which successfully leaves the simulational area.

An intermediate level of "panic", or in other words, an optimal mixture of pure self-control and control by the neighbors leads to a more efficient behavior. This may be a very general pattern for optimizing the collective behavior of groups.

## 4.4 NETWORKS OF PEOPLE

### 4.4.1 *Internet*

The many millions of people who are using the internet are forming a special community with its own rules and relations. Here we are considering one aspect, the structure of the network made of the home pages of the users and the links between these home pages. In particular we are interested in the statistical properties of

this graph, where the vertexes or nodes of the graph are the home pages and the bonds between the nodes are represented by a link pointing on one home page onto another home page (these are usually indicated by blue color and one can jump from one internet address (URL) to another one by simply clicking on this blue text).

A natural question to ask is the number of links pointing to a given home page. There will be home pages with a huge number of such links (these are popular, old home pages with a lot of information, like those of search engines, or internet journals, etc). There are much more single users with only a few others having a link on their home pages to these users. The quantity which can be used to describe the distribution of these links is  $n(l)$ , where  $n(l)$  is the number of nodes with  $l$  number of links pointing to them. For example,  $n(120) = 15600$  means that there are 15600 nodes (addresses) to which 120 links are established.

It is possible to construct little "robots" (to write programs) which browse the internet and record the links between nodes. After the data are collected, a histogram can be made. According to the latest analysis [9] the distribution  $n(l)$  follows a power law, it is proportional to  $l^{-2.1}$ . In other words, there are roughly four times less home pages with half as many links from other home pages. This distribution is very special and is rarely considered in social sciences, but is common in statistical physics (for example in the context of continuous phase transitions).

The origin of such a scale (typical size) free system in the present case is in the way it is generated. The internet is permanently growing by the addition of new nodes and links. The new links defined in new a node are preferentially pointed towards already popular, highly connected nodes. A simple probabilistic growth model based on these assumptions [6] leads to the above mentioned power law statistics.

Scale-free networks have very specific behaviours when their vulnerability in the in the context of intentional and unintentional attacks is considered (removal of highly connected or randomly selected nodes).

#### 4.4.2 *Scientific Collaborators*

A well defined and documented human network is made of the scientific collaborators, where the nodes are the authors and there is a link between two authors of they have published a paper together. We have constructed the corresponding graph [7] from data available for papers published in the fields of mathematics and neural sciences over the period 1992-2000.

On the basis of the several hundred thousand papers and authors we had data about we found that the above network of collaborators is scale-free as well. It seems that the probability, that a new author will publish together with an old author who has already had  $k$  collaborators is proportional to  $k$ . Moreover, the probability, that two authors having  $k_1$  and  $k_2$  coauthors typically write a paper together with a probability  $k_1 k_2$ .

The dynamics of the growth of such a human network can be modelled both by differential equations or Monte Carlo type stochastic growth models giving good agreement with the observations. It is amusing to detect that even such delicate human activities, as finding a partner for a creative enterprise is governed by the laws of statistical physics.

## 5. Conclusions

The models of collective behavior of humans can account for a number of specific features of social behavior under certain conditions. The advantage of the models is that by changing the parameters different situations can be easily created. Models adequately describing group phenomena can be used for predictions. In addition to such more concrete possible applications of simulations as the design of escape routes or better networks, the models are useful in providing a deeper insight into the mechanisms behind such collective phenomena as synchronization or panic.

## Acknowledgements

I thank the coauthors (of my related papers) for the fruitful and exciting collaboration.

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