A question of scale

Tamas Vicsek

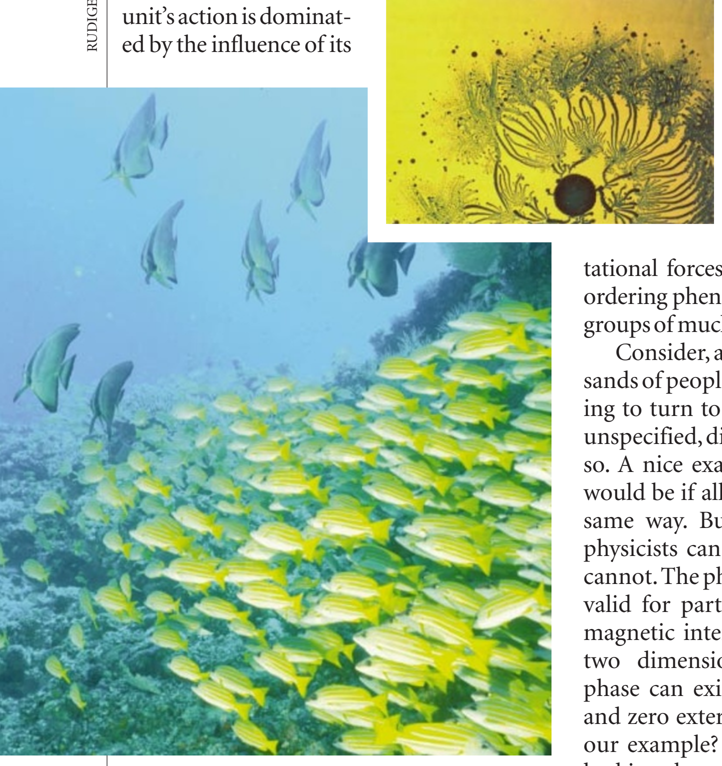
If you search the Internet for the phrase 'collective behaviour', most of what pops up will be about group activities of humans, including riots, fashion and mass panic. But collective behaviour is also an important aspect of observed phenomena in the world of atoms and molecules, for example during spontaneous magnetization. In your web search, you might also find articles on collectively migrating bacteria, insects or birds; or phenomena where groups of organisms or non-living objects synchronize their signals or motion — think of fireflies flashing in unison or people clapping in phase during rhythmic applause.

Is there a common factor in these seemingly diverse phenomena? The answer is yes — 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 can occur between neighbours in space or in an underlying network. Under some conditions, transitions can occur during which the objects adopt a pattern of behaviour almost completely determined by the collective effects of the other objects in the system.

The main features of collective behaviour are that an individual unit's action is dominated by the influence of its neighbours — the unit behaves differently from the way it would behave on its own; and that such systems show 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 small 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 spontaneously appears. Similarly, a group of feeding pigeons randomly oriented on the ground will order themselves into a uniform flock as they fly away after a big disturbance.

Collective behaviour applies to a great many processes in nature, which makes it an extremely useful concept in many contexts. Understanding a new phenomenon is usually achieved by relating it to a known one: a more complex system is understood by analysing its simpler variants. In the 1970s, there was a breakthrough in statistical physics in the form of the 'renormalization group method', which gave physicists a deep theoretical understanding of a general type of phase transition. The theory showed that the main features of transitions are insensitive to the details of the interactions between the objects in a system. This means that, as an extreme case, the orientational forces between atoms can result in ordering phenomena similar to those seen in groups of much more complex units.



All together now: collective behaviour can readily be seen in fish and bacteria (inset).

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Consider, as a thought experiment, thousands of people standing on a square and trying to turn to face the same, but externally unspecified, direction after being asked to do so. A nice example of collective behaviour would be if all of them managed to face the same way. But can they do it? Statistical physicists can predict for certain that they cannot. The physicists base this on a theorem valid for particles with short-range ferromagnetic interactions, which states that in two dimensions no long-range ordered phase can exist for any finite temperature and zero external field. So what happens in our example? On a small scale, people are looking almost in the same direction, but on a large scale, as seen from a helicopter for example, they form vortex-like directional patterns because of the small perturbations caused by human errors — just like the little magnets. But if people in the crowd are allowed to choose from a few discrete directions, the required ordering can be achieved.

Another recent theory surprisingly predicts that if the people are asked to move in the same spontaneously selected direction they can do it. Simulations and analysis of the related equations show that the motion of the individuals results in additional interactions, which enables information about local directions to spread through the whole system.

The approach of treating flocks, or even crowds, as systems of particles naturally leads to the idea of applying successful methods of statistical physics, such as computer simulations or theories on scaling, to the detailed description of the collective behaviour of organisms. Indeed, for the past couple of years — making use of collective behaviour — many interesting discoveries have been made for a rich variety of physical, animal and human behaviours.

We now have a much better understanding of collective phenomena such as aggregation, swarming and synchronization. For example, modelling the Internet's evolution shows that it is less sensitive to random, but more vulnerable to intentional, attacks than many other kinds of networks. Quantitative prediction of the collective reaction of people to situations including panic, and vehicular or pedestrian traffic is already possible in some cases. Using computer models to simulate cars or people as particles with appropriate interactions is soon expected to lead to better design of highways or hypermarkets. An improved, collective behaviour-based numerical analysis of situations involving higher-level human activities, such as fashion or outcomes of elections, may become feasible in the not-too-distant future. ■

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Collective behaviour

The way in which an individual unit's activity is dominated by its neighbours so that all units simultaneously alter their behaviour to a common pattern.

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FURTHER READING

http://angel.elte.hu/~vicsek
Coleman, J. S. *Foundations of Social Theory* (Belcamp Press, Cambridge, MA, 1990).
Huang, K. *Statistical Mechanics* (Wiley, New York, 1987).
Vicsek, T. (ed.) *Scaling and Fluctuations in Biology* (Oxford University Press, Oxford, 2001).