Table 1. Collision energy and the corresponding chemical potential μ_B

$\sqrt{s_{NN}}$ (GeV)	5.0	7.7	11.5	18	27	39
μ_B (MeV)	550	410	300	230	151	112

Data from Cleymans *et al.*[13].

to various $\sqrt{s_{NN}}$. Within the experimental statistics and kinematics range, we have not yet observed any nonmonotonic beam energy dependence. The results, $\kappa\sigma^2$, from three collision energies are consistent with unity, which could imply that the system is thermalized with a small value of correlation length. The results from non-critical point models are constant as a function of $\sqrt{s_{NN}}$ and have values between 1 and 2. The result from the thermal model is exactly unity. Within the ambit of the models studied, the observable changes little with a change in non-critical point physics (such as collective expansion and particle production) at the various energies studied. From comparison to models and the lack of non-monotonic dependence of $\kappa\sigma^2$ on $\sqrt{s_{NN}}$ studied, we conclude that there is no indication from our measurements for a critical point. Clearly the data at RHIC during 2010 and 2011 will be crucial to bridge the gap in baryon chemical potential regions to search for the critical point in the QCD phase diagram. Lattice QCD provides predictions for these ratios. Away from the critical point, the fireball is expected to come to thermal equilibrium and the lattice results should agree with observations. Near the critical point the fireball will fall out of equilibrium because of critical slowing down[8], and hence the lattice results would not describe the data. If a non-monotonic behaviour of the $\kappa\sigma^2$ is seen, then it will be clear that the system has passed or is close to the critical point.

Experimental status and plan

The experimental plan is to vary the centre of mass energy ($\sqrt{s_{NN}}$) of heavy-ion collisions to scan the phase plane and, at each energy, search for signatures of the critical point that might survive the evolution of the system. This programme has started and the first phase of the STAR experimental programme[4] at RHIC is expected to be completed in 2010–2011 (Table 1).

The second phase of the BES programme at RHIC will depend on the results from the first phase. Finer steps in the beam energies or μ_B, and focused analysis are envisioned. From the collider side, electron cooling is expected at RHIC in order to increase the luminosity at the low-energy region. We anticipate that the second phase of this programme will be carried out during the period 2014–2015.

1. The Frontiers of Nuclear Science, Nuclear Science Advisory Committee's December 2007 Long Range Plan; http://www.er.doe.gov/np/nsac/index.shtml
2. Adams, J. *et al.* (STAR Collaboration), *Nucl. Phys. A*, 2005, **757**, 102–183, and references therein; Braun-Munzinger, P. and Stachel, J., *Nature*, 2007, **448**, 302–309.
3. RHIC, http://www.bnl.gov/rhic/; NA49, http://na49info.web.cern.ch/; SHINE: https://na61.web.cern.ch/; CBM, http://www.gsi.de/fair/experiments/CBM/index_e.html and NICA, http://nica.jinr.ru/
4. Abelev, B. I. *et al.* (STAR Collaboration), *Phys. Rev. C*, 2010, **81**, 024911-1–024911-19 and references therein; Aggarwal, M. M. *et al.* (STAR Collaboration); arXiv:1007.2613.
5. Aoki, Y. *et al.*, *Nature*, 2006, **443**, 675–678.
6. Asakawa, M. *et al.*, *Phys. Rev. Lett.*, 2008, **101**, 122302-1–122302-4.
7. Gavai, R. V. and Gupta, S., *Phys. Rev. D*, 2008, **78**, 114503-1–114503-15; *Phys. Rev. D*, 2005, **71**, 114014-1–114014-21; arXiv:1001.3796; Gupta, S., arXiv:0909.4630; Fodor, Z. and Katz, S. D., *JHEP*, 2004, **0404**, 050-1–050-9.
8. Berdnikov, B. and Rajagopal, K., *Phys. Rev. D*, 2000, **D61**, 105017-1–105017-9.
9. Stephanov, M. A., *Phys. Rev. Lett.*, 2009, **102**, 032301-1–032301-4.
10. Asakawa, M. *et al.*, *Phys. Rev. Lett.*, 2009, **103**, 262301-1–262301-4.
11. Hatta, Y. and Stephanov, M., *Phys. Rev. Lett.*, 2003, **91**, 102003-1–102003-4.
12. Aggarwal, M. M. *et al.* (STAR Collaboration), *Phys. Rev. Lett.*, 2010, **105**, 022302-1–022302-6.
13. Cleymans, J. *et al.*, *Phys. Rev. C*, 2006, **73**, 034905-1–034905-10.

Bedangadas Mohanty is in the Variable Energy Cyclotron Centre, Kolkata 700 064, India.
e-mail: bedanga@rcf.rhic.bnl.gov

United we land: Statistical physics explains decision making in bird flocks

Anjan K. Nandi

Animals moving collectively are a spectacular sight. Flocks of flying birds (Figure 1), schools of fish, herds of quadrupeds – examples of coordinated movement in a group, are abundant in nature. Humans also sometimes display similar kinds of behaviour, like pedestrian motion, vehicular traffic movements, etc. Even at the microscopic level, bacteria are known to exhibit collective motion for their survival under unfavourable conditions. How do they manage to do so? This question has been of great interest to scientists for many years. It appears that all the individuals in a group get the information about what all the others are doing, and act appropriately. But for a very large group, this is not a plausible assumption. Then how do they take such decisions and coordinate themselves in an orderly manner? This phenomenon of creating order, such collective decision-making for example, out of an initial disordered situation comes in the realm of statistical physics. Therefore, it is not surprising that physicists have become interested in this field, which would otherwise be considered as the realm of animal behaviour.

In the statistical physics approach, the individuals, sometimes designated as agents, are taken to be particles who can interact with each other. Let us imagine a situation where each agent has to take a decision on a referendum and the choice is binary, for example, choosing between two brands of a newly launched product. If every agent takes an unbiased decision without being influenced by any factor, then about half of them will decide in favour of one brand, and the other half will choose the other brand. This is called a disordered state. But if the agent is influenced by the decision made by a certain number of other agents in its neighbourhood, then depending upon some conditions, a different state can be reached. Two parameters play important roles in this context. The first is the coupling strength that determines the propensity of the agents to follow the decisions of the other agents. The second is the environmental noise that affects the ability of the agents to correctly perceive the decisions of other agents. With a non-zero coupling and a low level of noise, agents become more likely to make the same choices as their neighbours and as a consequence, the system is driven towards an ordered state where most of the agents make similar choices. This transition from a disordered state to an ordered state has been studied for a long time using the Ising model (1925), which was originally formulated to explain how a piece of iron acquires magnetic properties. A lucid description of the model is available in Box 1.

Figure 1. A bird flock in collective motion (photograph by Souvik Mandal).

Box 1. The Ising model.

The model considers a crystal with N lattice sites, each site i being occupied by atoms (agents) of a magnetic material like iron. Each atom has a magnetic moment or spin s_i which can take any one of the two values, either +1 or –1. The total energy is defined as

$$H = -J \sum_{\langle ij \rangle} s_i s_j - h \sum_i s_i,$$

where the first sum is over all pairs of nearest neighbours, J is the coupling strength and h the applied magnetic field. Initially spins are randomly oriented and no net magnetic effect is seen. Keeping in mind that a lower energy state is always favourable, an ordered state can be achieved by the following procedure. A new state is reached after flipping a randomly selected spin. If the total energy of the new state is less than that of the previous state, the flipped state is kept, otherwise it is kept with a probability $\exp(-\Delta E/k_B T)$, where ΔE is the difference in energy, k_B the Boltzmann constant and T the temperature. Repeated application of the procedure will drive the system into one of the two ordered states, either majority +1 or majority –1, and a finite magnetic effect is seen. The temperature T introduces thermal noise into the system that drives the system away from order. There exists a critical temperature T_c above which no such ordering is possible. The transition point is characterized by the order parameter called magnetization $m = (1/N)\Sigma_i \langle s_i \rangle$, which is 0 for $T > T_c$ and greater than 0 for $T < T_c$, where $\langle \, \rangle$ denotes the average over many configurations.

The Ising model always assumes the agents as static objects, although for most biological phenomena involving collective decision-making, this is not a valid assumption – the biological objects always tend to move. The dynamics of collective motion was studied much later using the Vicsek model[1], where agents were considered as self-propelled particles (SPP) that move with a constant velocity and like the real organisms, are driven by some internal force produced by some internal energy. Each of them assumes the average direction of motion of the particles in its neighbourhood and tries to orient itself along that direction. Starting with a disordered state of randomly moving particles, a consensus analogous to the Ising model is reached after some relaxation time. This model was first successfully used to reproduce some observations of coherent motion in growing bacterial colonies[2] and can also be used to explain how a flock of flying birds makes collective movement in a particular direction.

There are still some problems to be solved. One is to maintain the cohesiveness of the groups. How do the birds manage to remain together as a flock? Why do they not disintegrate? Another important problem is to explain the swiftness of decision-making. How does a collectively moving flock of birds suddenly decide to land and actually perform the task? Or how does a school of fish moving in an orderly manner suddenly change direction? In spite of having differences in age, sex, social status or perception to external stimuli, they have been observed to take unanimous decisions abruptly, even in the absence of any global leader. These questions have been answered by Bhattacharya and Vicsek in a recent paper[3].

Box 2. Collective landing.

Birds are moving in a flock following the assumptions of the Vicsek model, that is, each of them assumes the average direction of motion of the birds in its neighbourhood of radius R, with a randomly added noise, which is taken from a uniform distribution in the range $[-\eta/2, \eta/2]$. The collective landing of the flock is explained using the basic framework of the random field Ising model[4] (RFIM), a variant of the well-known Ising model. Decision making by birds is characterized by the binary internal state variable s_i, with choices $s_i = 1$ when the ith bird continues to fly, and $s_i = -1$ when it decides to land. The landing surface is taken as $z = 0$. The motivational differences in birds, which resemble the 'random fields' of the RFIM, are introduced through an inherent switching time[5] t_i such that, starting the flight at time $t = 0$, the bird would decide to land at time $t = t_i$. These t_is are taken from a Gaussian distribution with standard deviation σ_0. The average decision of the birds in the neighbourhood $N(i, R)$ of radius R of the ith bird at time t is given by a local mean field $S_{N(i,R)}(t)$ such that when the birds are continuing to fly, $S_{N(i,R)}(t) \sim 1$ and decision in favour of landing would imply $S_{N(i,R)}(t) \rightarrow -1$. The internal state is described by the expression:

$$s_i(t) = \text{sign}[t_i - t + JS_{N(i,R)}(t - \Delta t)],$$

where J is the coupling strength. Successful collective landing will depend on the parameters η, R, σ_0 and J.

In Figure 2 *a*, the fraction of birds in flight $A_J(t)$ is plotted with time t for different coupling values J. When no coupling is present, that is $J = 0$, birds switch their states independent of each other and the curve $A_0(t)$ shows slow transition. But when $J = 2\sigma_0$, a sharp fall can be seen in the curve $A_{2\sigma_0}(t)$, indicating that a large number of birds collectively decide to land within a short period of time and at a time when about half of the birds would have just crossed the inherent switching times. The curve $A_{10\sigma_0}(t)$ for higher coupling values also shows a similar transition, but delayed in time. Unlike $A_{2\sigma_0}(t)$, the fraction of birds $S_{2\sigma_0}(t)$ deciding to land at time t with coupling $J = 2\sigma_0$ is seen to fluctuate because of the noise and fluctuations in the vertical motion of the neighbours. Bhattacharya and Vicsek[3] have shown that due to the larger fluctuations, a better interaction between choices occurs and the spatial spreading of the landed flock becomes smaller. Figure 2 *b* shows the snapshot when most of the birds decide to land. Bhattacharya and Vicsek[3] also rigorously explored the role of the various parameters in the transition. They found a characteristic value of heterogeneity below which flocks remain spatially coherent in the process of landing, above which it is lost.

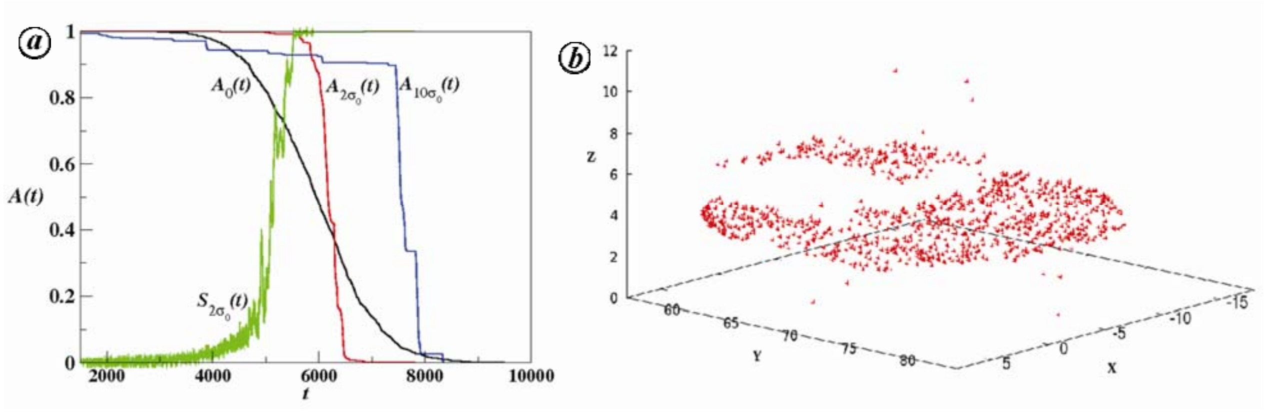

Figure 2. ***a***, The fraction of birds in flight $A(t)$ and fraction of birds showing intention to land $S(t)$ are plotted against time for different coupling values $J = 0$, $2\sigma_0$ and $10\sigma_0$. ***b***, A snapshot of collective landing of a flock of birds with 1024 agents. Arrowheads pointing towards the direction of motion (reproduced from ref. 3 with permission).

The authors have presented a novel model for the landing of a cohesive flock of birds. The starting point is the Vicsek model, with the birds collectively moving towards a certain direction. Environmental noise may prevent the birds from correctly perceiving the motion of other birds. As a result, the flock may tend to break up into smaller sub-flocks moving in independent directions. The authors have introduced a new kind of 'co-moving boundary' condition which ascertains that, when a bird tries to cross the boundary of the flock, it immediately gets an alert through an attractive force. This force brings the bird back into the flock and therefore prevents the flock from fragmentation.

Next, to explain the most important problem, collective landing, the following assumptions are made. While in flight, the birds meet with a binary choice problem, either to continue their flight or to decide in favour of landing, just like the basic Ising model. Again the decisions are influenced by the local neighbourhood interactions and environmental noise. When most of the neighbours are in motion, a bird is likely to continue its flight and when most of them start to land, the bird is also likely to decide in favour of landing. But when exactly do they decide to land? The model further assumes that the birds have different internal-energy reserves and when a bird is on the verge of exhausting its energy, it decides to land. To incorporate this effect, the authors have introduced an additional motivational parameter such that a bird with a lower parameter value would try to land more quickly than the others. The parameter also includes the effect of environmental stimuli like foraging patches over which the flocks fly. The exact moment of collective landing is determined through a competition between the above parameters. A strong motivation in favour of landing can be overridden by the presence of strong propensity to follow the flying neighbours. The authors have shown using computer simulations that, while in the absence of coupling, birds land only due to the individual motivations and independent of each other, and in the presence of coupling, the model results in a realistic dynamics where in spite of having a large variation in motivation, an abrupt collective landing is well possible. A further and more technical description of the model can be found in Box 2.

Bhattacharya and Vicsek[3] have combined the dynamics of collective motion and the process of collective decision-making in a single model. Applications of this model can reach well beyond the regime of animal behaviour. This model can be used to study phenomena like sudden changes in the minds of voters or consumers, emergence of panic in a crowd, sudden outbreak of epidemic or rumour, instantaneous changes of state in robotic groups – spanning fields like sociology, economics, psychology, control theory and crowd management, to name a few. We look forward to many more interesting studies that would unravel other natural or social phenomena with the help of this model.

1. Vicsek, T., Czirok, A., Ben-Jacob, E., Cohen, I. and Shochet, O., *Phys. Rev. Lett.*, 1995, **75**, 1226–1229.
2. Ben-jacòb, E., Shochet, O., Tenenbaum, A., Cohen, I., Czirok, A. and Vicsek, T., *Nature*, 1994, **368**, 46–49.
3. Bhattacharya, K. and Vicsek, T., *New J. Phys.*, 2010, **12**, 093019.
4. Michard, Q. and Bouchaud, J.-P., *Eur. Phys. J. B*, 2005, **47**, 151–159.
5. Conradt, L. and Roper, T. J., *Nature*, 2003, **421**, 155–158.

ACKNOWLEDGEMENT. I thank Dr Kunal Bhattacharya (Eötvös University, Hungary), Dr Anindita Bhadra (IISER, Kolkata) and Prof. Raghavendra Gadagkar (IISc, Bangalore) for their critical feedback.

Anjan K. Nandi is in the Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560 012, India.
e-mail: anjanandi@gmail.com