ification of existing terms. Finally, Bjørnstad *et al.* apply a statistical method to their raw data, and confirm the findings based on the time-series method and the population model.

We do not yet know how useful Bjørnstad *et al.*'s methods will be in identifying the important variables in other systems, including natural ones. Theory predicts[6] how the dynamics of a population will be affected by the strength of coupling between two species. But it is not yet clear whether coupling to more and more variables inexorably increases the number of lags.

However, on the empirical front, thousands of sets of population data exist[7]. Although it would take a herculean effort to analyse them all, breakthroughs may be in the offing. The same group previously showed[8] that by increasing the depth of *P. interpunctella*'s artificial diet, the wasps' attack rate could be diminished, resulting in a weaker effect on the moth's population dynamics. Combining this system with the new analysis techniques will provide an opportunity to test whether varying a habitat parameter affects the strength of coupling of the system. The prediction here is that coupling between moth and wasp population dynamics should decrease as diet depth increases.

There are also broader implications. The group previously found[5] that when both virus and wasp confront the moth together, the simple generation cycles found in the one- and two-species systems are thrown out of whack: the three-species system exhibits transient cycles of longer periods, and eventually becomes extinct. If the imprints of one or both enemies on these cycles could be found, we would be a step closer to knowing whether Bjørnstad *et al.*'s techniques can be applied to biodiversity and conservation research, where one might want to know how a species that is harmless in one context can lead to the collapse of part of a community in another. These techniques could also be used to show how the use of two natural enemies as biological pest controls yields outcomes that are qualitatively different to the outcomes of using either enemy alone[9]. ■

Michael E. Hochberg is at the Institut des Sciences de l'Evolution, Université de Montpellier II, 34095 Montpellier, France.
e-mail: hochberg@isem.univ-montp2.fr
Arthur E. Weis is in the Department of Ecology and Evolutionary Biology, University of California, Irvine, California 92697, USA.
e-mail: aeweis@uci.edu

1. Bjørnstad, O. N., Sait, S. M., Stenseth, N. C., Thompson, D. J. & Begon, M. *Nature* **409,** 1001–1006 (2001).
2. Woiwood, I. P. & Hanski, I. *J. Anim. Ecol.* **61,** 619–629 (1992).
3. Strong, D. R. *Trends Ecol. Evol.* **1,** 39–42 (1986).
4. Turchin, P. *et al. Nature* **405,** 562–565 (2000).
5. Begon, M., Sait, S. M. & Thompson, D. J. *Nature* **381,** 311–315 (1996).
6. Tanner, J. T. *Ecology* **56,** 855–867 (1975).
7. NERC Centre for Population Biology, Imperial College. The Global Population Dynamics Database (1999). http://cpbnts1.bio.ic.ac.uk/gpdd/
8. Begon, M., Sait, S. M. & Thompson, D. J. *Proc. R. Soc. Lond. B* **260,** 131–137 (1995).
9. Murdoch, W. W. & Briggs, C. J. *Ecology* **77,** 2001–2003 (1996).

Turbulence

Go with the flow

Itamar Procaccia

Traditional devices for measuring turbulence have been unable to keep up with the latest developments in theory. But detectors derived from high-energy physics may narrow the gap between experiment and theory.

Turbulence is the chaotic and unpredictable motion of fluids flowing at high rates. It plays a major role in many processes from the environmental, for example cloud formation, to the technological, such as in industrial chemical reactors. Clearly, a deeper understanding of this phenomenon would be beneficial, and in recent years much progress has been made in the fundamental theory underlying turbulence. But the ability to measure turbulence experimentally has not advanced at the same rate, making it difficult to verify the theoretical developments.

On page 1017 of this issue, Eberhard Bodenschatz and collaborators[1] report an important technical improvement to the way in which turbulence is measured. This advance may make a decisive contribution to bringing experimental turbulence research back on par with theory.

In their experiment, Bodenschatz and co-workers[1] modified a detector from Cornell's electron–positron collider. They used 'silicon strip' detectors to optically image tracer particles (tiny transparent beads) in turbulent water flow. Compared with previously available techniques, this method offers unprecedented time resolution of up to 70,000 frames per second. As a result, the researchers were able to measure the acceleration of the particles in turbulent water, discovering that it can reach 1,500 times the acceleration of gravity. The high time-resolution of the measurements indicates that the acceleration is highly intermittent, reflecting the complex structure of turbulent flow.

At present, the standard probe for turbu-

100 YEARS AGO

A simple workable, absolutely trustworthy system is still urgently wanted for the detection of criminals, and if the authoress of this book has succeeded she certainly deserves the thanks of all the Governments of Europe… It so happened that about seven years ago the reviewer came to the conclusion that the external ear ought to yield some clue to the relationship of man and ape, and of one race of man to another… To test the "criminal-mark" theory of Lombroso and many others, he examined the ears of more than 800 confirmed criminals, and of more than two thousand inmates of asylums for the insane, situated in parts of the country where he had already examined the ears of the sane. Altogether the ears of more than 40,000 people of different races and of different moralities, besides those of about 300 apes and anthropoids, were examined, but the total results of this elaborate investigation were almost entirely of a negative nature… If the reviewer's methods and observations are correct, the confirmed criminal's ear is the ear of the average inhabitant of Great Britain. Nor did the ears of the insane differ, on an average, from those of the people from which they were drawn, and if the authoress had carried her observations over a number of men of genius or of high ability, instead of drawing elaborate deductions from single observations, she would probably have arrived at a similar conclusion as to them.
From *Nature* 21 February 1901.

50 YEARS AGO

Miss Dorothea M. A. Bate, who died after a brief illness on January 13 at the age of seventy-two, was for more than fifty years one of the outstanding personalities at the British Museum (Natural History). When only seventeen, and with neither qualification nor encouragement, she started work in the Bird Room as a voluntary worker; but her interests lay chiefly in palaeontology in relation to the Recent fauna, rather than in the Recent fauna itself… During 1901–1902 Miss Bate explored the caves of Cyprus and made some notable discoveries, such as the remains of pigmy elephants, and soon extended her interest to cave deposits in Crete, the Balearic—where she discovered the unique 'antelope' *Myotragus*—Malta and Sardinia, working meticulously and earnestly and always alone.
From *Nature* 24 February 1951.

lence research is the hot-wire anemometer. This consists of a thin wire that is heated by the passage of an electrical current and is kept at a constant temperature by means of a feedback loop. The wire is placed at right angles to the average flow of a turbulent fluid. The fluid cools the wire and, because the cooling effect depends on the fluid's velocity — the faster the fluid flows, the more the wire is cooled — the velocity can be measured as a function of time. As would be expected for turbulent fluids, an erratic time series is obtained.

Hot-wire technology has progressed in recent years: for example, superconducting elements have been used to measure the velocities of cryogenic helium turbulence[2]. But this technology gives only limited information on the structure of turbulence. Hot-wire anemometry is fundamentally limited: it can provide data only for a fixed point — in other words, for the point at which the wire is positioned. But theorists dream about measuring scale-dependent information from points that move with the flow — the so-called 'lagrangian' trajectories (Fig. 1).

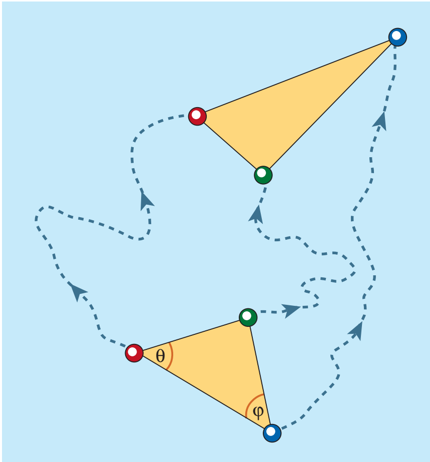

Figure 1 **The lagrangian evolution of a group of three tracer particles. At any moment in time the trio defines a triangle that is fully determined by a scale *R*, the Euler angles of its orientation in space, and two internal angles. Theory focuses on 'statistically preserved structures' which are determined by the distribution on internal angles and the scale. These structures dominate the statistical theory.**

Turbulent flow is irregular and disordered, with particles experiencing many different velocities. At large scales, the chaotic flow of the fluid demonstrates the presence of high amounts of energy. But instability results in energy loss, which cascades nonlinearly down to smaller scales. This cascade continues down to the smallest scale where molecular friction comes in and energy is dissipated by viscosity. The most interesting regime to study covers the intermediate scales, where the presence of a constant energy flux from large to small scales establishes a statistical equilibrium inside the fluid. For theoretical calculations, the mean velocity of the fluid is subtracted from the turbulent flow by a 'galilean' transformation. Theorists focus on the lagrangian trajectories in the moving frame of the fluid, and are interested in measuring the physical phenomena in this lagrangian picture. The technique devised by Bodenschatz and co-workers brings us closer to this dream.

Hot-wire anemometry would be quite useless for turbulence research had it not been for the ingenuity of G. I. Taylor, who pointed out that when the mean velocity of the fluid is very high, the time series measured at a point can be considered as a spatial cut through the turbulent field. This 'Taylor frozen turbulence hypothesis' asserts that the turbulent field is swept through the probe faster than the field can appreciably change, so the wire is taking a one-dimensional 'snapshot' of the velocity field. This has been the basis for analysis of turbulence data for decades, but besides being only approximately true, recent theoretical work has drawn attention to essential features of turbulence that are totally missed by measuring one-dimensional cuts (Box 1).

But Bodenschatz and co-workers offer new possibilities in following the detailed motion of fluid particles. This progress promises an exciting and fruitful interaction between theory and experiments in turbulence in the coming years. ■

Itamar Procaccia is in the Department of Chemical Physics, The Weizmann Institute of Science, Rehovot 76100, Israel.
e-mail: itamar.procaccia@weizmann.ac.il

1. La Porta, A., Voth, G. A., Crawford, A. M., Alexander, J. & Bodenschatz, E. *Nature* **409**, 1017–1019 (2001).
2. Tabeling, P. *Phys. Rev. E* **53**, 1613–1621 (1996).
3. Bernard, D., Gawedcki, K. & Kupiainen, A. *J. Stat. Phys.* **90**, 519–569 (1998).
4. Gat, O., Procaccia, I. & Zeitak, R. *Phys. Rev. Lett.* **80**, 5536–5539 (1998).
5. Frisch, U., Mazzino, A. & Vergassola, M. *Phys. Rev. Lett.* **80**, 5532–5535 (1998).
6. Arad, I. & Procaccia, I. in *Proc. IUTAM Symp. Geom. Stat. Turb.* (ed. Kambe, T.) 175–184 (Kluwer, Dordrecht, 2001).
7. Celani, A. & Vergassola, M. *Phys. Rev. Lett.* **86**, 424–427 (2001).
8. Arad, I., Biferale, L., Celani, A., Procaccia, I. & Vergassola, M. (submitted).

Box 1 A problem to be solved

One of the theoretical problems that can be verified experimentally using the techniques developed by Bodenschatz and co-workers[1] involves an important aspect of turbulence: its role in dispersing contaminants such as smoke or radioactive elements in the air and pollutants in the ocean. The concentration of such a contaminant at a space point $\boldsymbol{r}$ at time t is denoted as $T(\boldsymbol{r},t)$. One may be interested in the expected value of the field at some point $T(\boldsymbol{r}_3,t)$ given the measurement of the concentration at two other points $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ at the same time. Such expected values are related to 'correlation functions'. In this example, we have a third-order correlation function which is denoted as $<T(\boldsymbol{r}_1,t)\ T(\boldsymbol{r}_2,t)\ T(\boldsymbol{r}_3,t)>$ where the averaging is over time.

Central to the statistical theory of turbulence is the finding that such correlation functions show a remarkable property called 'scaling'. This means that if we increase all the distances between the measurement points $\boldsymbol{r}_1$, $\boldsymbol{r}_2$ and $\boldsymbol{r}_3$ by a given factor λ, then the value of the correlation function changes by a multiplicative factor λ^{ζ_3}, where ζ_3 is a characteristic exponent. If we consider higher-order correlation functions between four, five or n points, they have the same property but with exponents ζ_n that depend on the order of the correlation function. These scaling exponents ζ_n are believed to be universal characteristics of the small-scale structure of the turbulent velocity field, reflected in the structure functions of advected contaminant. Their theoretical calculation is much sought after in fundamental turbulence research.

In recent years there has been a fundamental shift in the theoretical approach to such characteristics of turbulence[3]. It turns out that the nature of these exponents is related to subtle geometrical properties of groups of lagrangian trajectories of tracer particles[4,5]. For example, to understand the exponent ζ_3 one needs to focus on the dynamics of three tracer particles. Obviously, at any point in time three tracer particles define a triangle, which in turn is fully characterized by one length scale R (say the geometric mean of the lengths of its sides) and two angles, say θ and ϕ. When the three tracer particles are advected by the turbulent velocity field (see Fig. 1 on page 1017 for the lagrangian trajectory of one such particle), the scale R of the defined triangle and its shape (angles) change continuously (Fig. 1). If we rescale the triangle to size $R=1$, the dynamics become a trajectory in the space of shapes[6], the space of all triangles of size 1 (conveniently characterized by two angles θ and ϕ). These dynamics have equilibrium distributions given by $\rho(\theta,\phi)$. The deep and surprising new statement that can be made is that the three-point statistics are dominated by trajectories in which the change in R is compensated by a change in shape so that $R^{\zeta_3}\rho(\theta,\phi)$ remains invariant[7].

Such 'statistically preserved structures' are crucial for the statistical theory, as they obviously come to dominate the statistics[8]. Indeed, exponents such as ζ_3 can be understood as the rescaling exponents characterizing precisely such special distributions: the correlation function $<T(\boldsymbol{r}_1,t)\ T(\boldsymbol{r}_2,t)\ T(\boldsymbol{r}_3,t)>$ is proportional to $R^{\zeta_3}\rho(\theta,\phi)$, where R is the geometric mean of the distances between the points $\boldsymbol{r}_1 \ldots \boldsymbol{r}_3$. Of course, the same ideas apply to any order correlation function or structure functions with the appropriate shape dynamics, and they quickly become the new language used to discuss scaling phenomena in turbulent transport[7,8]. **I.P.**