Unweaving the whirls

Turbulence

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Joël Sommeria

Turbulence denotes complex fluid motion, as opposed to smooth laminar flows. It evokes agitation, disorder and chaos. The definition of chaos restricts it to dynamic systems of which only the time behaviour is complex — deterministic but sensitive to the initial condition. Turbulence involves spatial as well as temporal complexity, with 'fractal' multi-scale velocity fields.

Although physics is successful in grasping many remote and extreme phenomena, it is often of little help with common problems encountered in life. In *De rerum natura*, Lucretius describes the random motion of dust seen in a ray of sunlight, an early hint at the motion of atoms in a vacuum. Yet nowadays, we know more about atoms than about the turbulent air motion revealed by dust.

The relevant laws of mechanics have been known since Newton's time; the resulting partial-differential equations for a fluid were derived by Leonhard Euler, with a viscous term introduced by Claude-Louis Navier in 1823. Turbulence is supposedly included in these equations as complex, unsteady flow solutions. Modern computers have begun to grasp this complexity, but the available spatial resolution is still too low for a full model of the air flow in a room. We need to resolve the scale on which viscous smoothing occurs — just a few millimetres — and we also need to determine the initial condition. But measuring such three-dimensional velocity fields is beyond the ability of current technology.

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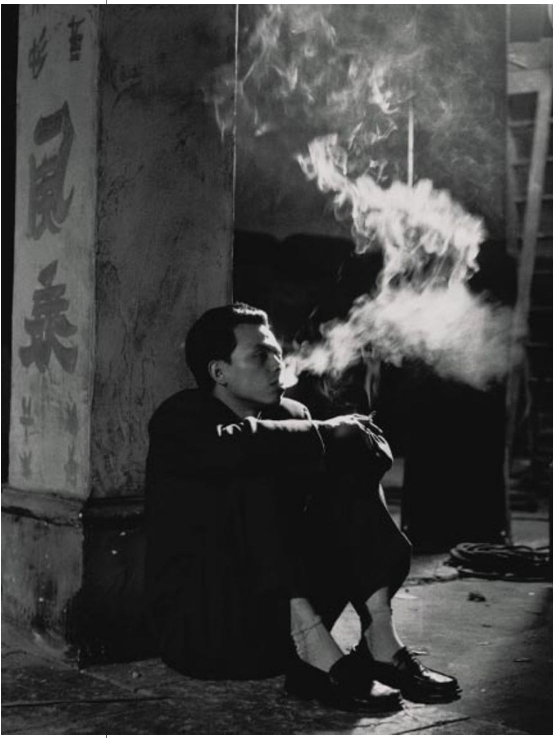

Up in smoke: the erratic motion of the particles reveals the turbulence of the surrounding air.

A direct numerical simulation would provide gigabytes of raw data, but this would just be the starting point. Statistical properties, such as mean transport of air mass, of temperature and of chemicals, must be considered. Wall friction and noise emission (pressure fluctuations) are relevant in aerodynamics. The gradients of wind and concentration of transported chemicals have intriguing, intermittent fluctuations, which can control chemical reactions. The emergence of coherent flow structures is also remarkable, but is often difficult to characterize unambiguously.

'Predictability' expresses the sensitivity of predictions to a small initial perturbation, or error — thereby imposing, for example, limitations on meteorological forecasts. Exponential error growth (chaos) is observed in simplified models that retain only the largest scales of motion. (This has been popularized as the 'butterfly' effect, from the legend about a butterfly wingbeat eventually modifying the weather.) This is unlikely, however, as such unpredictability is overestimated in models that are simplified to a few dynamic variables describing only large scales. In reality, the global effects of many small-scale perturbations tend to be predictable. Likewise, colliding molecules have highly unpredictable motion, but collectively give rise to the very predictable properties of gases.

Sensitivity to physical perturbations (for instance, vibration at a wall) is also a key issue, about which laboratory experiments provide valuable information. Turbulence is therefore a genuine scientific field, involving experiments, theory and numerical simulations. Although it relies on classical mechanics equations, the solutions of which are approached by computation, conceptual understanding is needed. This is essential not only in engineering design — for instance in improving aerodynamics by active control of boundary layers — but also for modelling the evolution of our natural environment.

In the early Universe, turbulence controlled the development of density fluctuations that eventually led to the formation of galaxies. Similarly, it governs the development of fluctuations in molecular clouds at the origins of stars, as well as the accretion of protoplanetary nebulae and the agglomeration of dust that leads to planetary formation. Climate changes are governed by turbulent fluctuations in the Sun, the atmosphere and the oceans, and the melting of polar ice caps is controlled by turbulent heat transfer.

The concept of eddy viscosity (and diffusivity) is widely used to model the effects of the small, unresolved scales of turbulence in 'large eddy simulations'. Navier derived his expression of viscosity as an effect of unspecified random transport; such arguments were later formalized by James Clerk Maxwell and Ludwig Boltzmann in the kinetic theory of gases. The statistics of a continuum fluid motion pose a quite different problem: unlike molecules, fluid elements interact over long ranges (by pressure force) and deform irreversibly.

In two dimensions, the vorticity (curl of velocity) of each fluid element is conserved. The system is therefore like a set of elementary vortices (spinning-tops) with a long-range interaction. Statistical equilibrium states involve clusters of aligned elementary vortices. This explains the persistence of large, coherent vortices, such as Jupiter's Great Red Spot, in turbulent atmospheres and oceans.

But the most common form of turbulence is three-dimensional and far from equilibrium, with an irreversible cascade of energy towards small scales. Andrei Kolmogorov described this cascade in 1941, arguing that the dynamics are scale-independent. However, this is only approximately true. Deviations have been obtained, in the form of intermittency exponents, for transport of a pollutant by a random gaussian velocity (simplified synthetic turbulence). Extension of these descriptions to turbulent flow itself would be a great achievement, but not the whole story.

Real turbulent flows are diverse, depending on boundary effects, rotation and external forces (such as buoyancy). Randomness is not externally imposed, but rather spontaneously arises. There will be no single breakthrough — we face deep questions about information processing and probabilities, and about the very meaning of scientific understanding and prediction. Turbulence allows us to venture towards this new frontier with the safeguard of rigorous classical mechanics. ■

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FURTHER READING:

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