Transition to turbulence

As any physicist knows, fluid in a pipe can flow smoothly at sufficiently low speeds, as parcels of fluid trace out continuous streamlines. At higher speeds, the simple flow often becomes turbulent, with fluid elements now moving on disorderly, chaotic paths. In 1883, the British physicist Osborne Reynolds tried to clarify details of this transition, along the way introducing his Reynolds number, Re, as a key dimensionless quantity characterizing flows by the relative importance of inertial and viscous forces.

Today, physicists still lack a theory, based on first principles, explaining the nature of this transition. Even so, remarkable progress has been made in the past decade, and turbulence in pipe flow is finally yielding some of its secrets.

Naively, one might imagine that the stable, laminar flow simply becomes unstable at sufficient flow speeds — or, equivalently, a high enough Reynolds number, Re. Yet, according to the Navier-Stokes equations, the laminar state is in fact always linearly stable. When disturbed vigorously, turbulence in pipes begins at Re ~ 2,000, whereas in especially quiescent conditions, the transition can be delayed to Re ~ 12,000 or even higher.

This confusing situation motivated Reynolds in his 1883 work to define the turbulent transition — linked to the critical Reynolds number, Re$_c$ — as the point beyond which turbulence, once started, will persist indefinitely. Turbulence can exist, or not exist, both below and above the critical threshold. For Re < Re$_c$, it always dies out eventually, while for Re > Re$_c$, turbulence once created persists.

So how does this transition come about? In a series of experiments over the past decade, physicists have pinned down a number of telling empirical details. To begin with, at low Re, turbulence always settles into a simple form — it exists not as a spatially extended pattern, but in localized 'puffs', separated by laminar zones. The typical lifetime of a puff seems to increase with Re in a faster-than-exponential way. Even so, this lifetime — at least within the limits of experiment — always remains finite (B. Hof *et al.*, *Nature* **443,** 59–62; 2006).

One might have imagined persistent turbulence arising from a finite Re divergence of this lifetime, but that is not the case. Rather, something else seems to happen: puffs at higher Re not only last

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longer, but also begin to split apart, making turbulence spread. The rate at which puffs split apart also increases with Re, again in a faster-than-exponential way (K. Avila *et al., Science* **333,** 192–196; 2011), and it is the combination of these two trends — puffs lasting longer and splitting more quickly — that lies behind the transition to lasting turbulence. Below the critical Re, puffs die out more quickly than they split to generate new ones. Turbulence dies out. Above the critical Re, the splitting happens faster than the dying out, and turbulence persists.

Intriguingly, there is a close similarity with the dynamics of epidemics. Moving Re up through the critical value is like increasing the basic reproduction number for an infectious agent through the critical point so that each new infection ultimately creates more than one further infection, and the agent becomes endemic.

This picture of turbulence gains further support from theoretical approaches. Thirty years ago, French physicist Yves Pomeau suggested that the coarse-grained features of how turbulent and laminar zones mingle in regimes of mixed flow might act like patterns in so-called directed percolation. This is a fundamental stochastic spreading process linked to phenomena ranging from fluid movement through porous media to forest fires. Inspired by this idea, mathematician Dwight Barkley of the University of Warwick recently proposed a model for pipe flow in which turbulent puffs behave rather like action potentials in nerve axons. The state of linearly stable laminar flow would be the medium rest state, with turbulence the excited state.

A model based on this picture (D. Barkley *Phys. Rev. E* **84,** 016309; 2011) shows a continuous transition to sustained turbulence at a critical value of Re$_c$. The mean puff lifetime grows with Re, as does the rate of splitting, and just above Re$_c$, a puff is more likely to split than to decay. Just above the critical point, Barkley found, the fraction of fluid in the turbulent phase grows as $(\mathrm{Re} - \mathrm{Re}_c)^{0.28}$. This is just as expected if the transition really is in the class of directed percolation, as Pomeau proposed. More recently, Barkley and colleagues have taken this approach further (D. Barkley *et al. Nature* **526,** 550–553; 2015), offering a simple dynamical system that accounts for even more features of pipe flow, including how puffs grow wider with time as they flow downstream.

An alternative — and quite different theoretical perspective — points to directed percolation as well. Nigel Goldenfeld and colleagues (*Nature Phys.* http://doi.org/96m; 2015) ran numerical simulations of pipe flow and tried to identify the most important non-turbulent collective modes. These turned out to be so-called 'zonal flows' representing azimuthal modulations of the basic laminar flow pattern. These zonal flows represent important coherent ways that energy often seems to get organized in these pipe flows.

From these observations, the researchers noted that these zonal flows compete with turbulence following a basic predator–prey interaction. In this picture, the basic laminar flow is akin to a nutrient, which turbulence (the prey species) feeds on and spreads. In turn, turbulence can be fed on by the zonal flows (the predator species). Studying the simplest model for such interactions, the authors found that it leads to distributions of puff lifetimes and splitting times that look very much like those found for pipe flow. In this case, the parameter playing the role of Re is the prey (or turbulent puff) birth rate.

Again, as it turns out, this simple predator–prey model maps onto a statistical model in the directed percolation class. So Pomeau's conjecture seems to be on target, and supported from two different points of view. It seems that at least one small part of the long quest to understanding the transition to turbulence may be coming nearer to a close. At the same time, much less remains known about turbulence at very high Re, far away from the transition regime.

These results are also satisfying as directed percolation is thought to be the general universality class for non-equilibrium phase transitions with an absorbing state — a state that, once entered, is never left. Surprisingly, turbulence in pipe flow may be the first good experimental example. ❐

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