soon be sufficiently accurate to provide a statistically significant value of the fine-structure constant (*3*), which would be the first time in many decades that it could be based on actual atomic fine structure.

Another remarkable attainment of precise atomic spectroscopy is the measurement of nuclear properties by high-resolution measurements of electronic transitions. The effects of finite nuclear size show up as tiny perturbations in the energy levels, which can be analyzed quantitatively if sufficiently accurate atomic structure calculations can be completed. Van Rooij *et al*. have compared the 2 $^1S \rightarrow$ 2 ^3S frequencies in ^3He and ^4He to accurately determine a ^3He nuclear charge radius of 1.961(4) fm. The result is more accurate than direct measurements by scattering of energetic electrons (*4*), although it disagrees with a previous atomic physics determination.

Looking ahead, the authors have also set the stage for a new generation of deep-ultraviolet (UV) measurements that would probe ultracold helium atoms in the ground 1 ^1S state, which lies below the metastable states by a remarkably large 20 electron volts (eV). If newly developed UV frequency combs can be used directly for such measurements, improvements in accuracy by many orders of magnitude would be possible (*5*, *6*). The first major step toward this goal is to produce an optically trapped sample of ultracold atoms in the singlet metastable state. This could be achieved by a variation of the arrangement used by van Rooij *et al*., which already can transfer the entire trapped atom sample to the 2 ^1S state. Unfortunately, their present 1.55-μm trap is repulsive for 2 ^1S atoms, so a different trapping wavelength would be necessary. It can be expected that cold singlet-state helium atoms will soon be available for spectroscopy and cold collision experiments, and ultimately for the production, trapping, and spectroscopy of the ground state.

References

1. R. van Rooij *et al*., *Science* **333**, 196 (2011).
2. G. Łach, K. Pachucki, *Phys. Rev. A* **64**, 042510 (2001).
3. K. Pachucki, V. A. Yerokhin, *Phys. Rev. A* **79**, 062516 (2009).
4. C. R. Ottermann *et al*., *Nucl. Phys. A.* **436**, 688 (1985).
5. E. E. Eyler *et al*., *Eur. Phys. J. D* **48**, 43 (2008).
6. D. Z. Kandula, C. Gohle, T. J. Pinkert, W. Ubachs, K. S. E. Eikema, *Phys. Rev. Lett.* **105**, 063001 (2010).
7. National Institute of Standards and Technology (NIST) Atomic Spectra Database Version 4, NIST Standard Reference Database 78; www.nist.gov/pml/data/asd.cfm (2010).
8. G. Łach, K. Pachucki, *Phys. Rev. A* **64**, 042510 (2001).
9. S. A. Alexander, R. L. Coldwell, *Int. J. Quantum Chem.* **108**, 2813 (2008).

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APPLIED PHYSICS

A Critical Point for Turbulence

Bruno Eckhardt

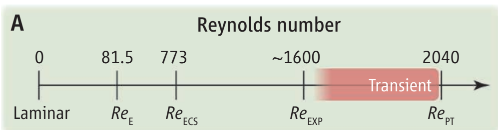
The conditions that mark the transition from laminar to turbulent flow in a pipe have been determined by experiments and numerical simulations.

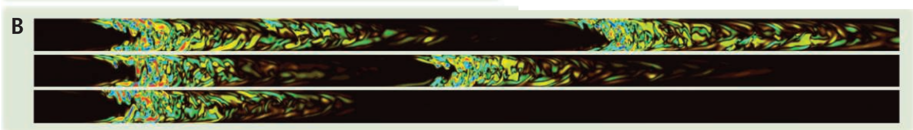
When a wind goes from a gentle breeze to a gusty storm, it changes from a state of smooth laminar flow to one that is complex and turbulent. One of the great triumphs of early 20th-century science was determining the exact conditions for the occurrence of the transition between these dynamical states for many types of flows (*1*). For most cases, a well-defined critical flow speed could be determined where laminar flow becomes susceptible to small perturbations and gives way to turbulence. One of nature's whims is that the technologically important case of pressure-driven flow through a cylindrical pipe does not fit into this classification (*2*). On page 192 of this issue, Avila *et al*. (*3*) show how a critical point for turbulent pipe flow may finally be identified.

Avila *et al*. studied the flow of water at speeds of about 0.5 m/s in a pipe 4 mm in diameter and 15 m in length. All of these dimensional quantities can be combined into a single relevant dimensionless parameter, the Reynolds number $Re = UD/\nu$, formed by the mean velocity U, the diameter D of the pipe, and the kinematic viscosity ν of the fluid. A transition from laminar to turbulent flow is often observed near Re of about 2000, but the quoted values vary considerably, not only between publications or experimental facilities but also between runs at the same facility (*2*). So should this be construed as a transition without a critical point?

Most of the progress made in characterizing transitions was achieved by studying the response of the laminar flow state to small perturbations, which are expected to decay below the critical Reynolds numbers and to be amplified above it. Fluid flows are described by the Navier-Stokes equations, which are nonlinear partial differential equations that can be solved exactly for a limited set of conditions only. For small perturbations in the vicinity of the laminar flow, linearized flow equations that are more readily solved provide an approximate description (*1*). However, calculations for pipe flow show that there is no change in behavior and that no critical point can be found this way. The sufficiently small perturbations required for a linear analysis will always decay at arbitrarily high Reynolds numbers (see the figure, panel A) (*4*).

Turbulence can only arise through large perturbations for which the full nonlinear equations of motion have to be studied. Direct numerical simulations of the Navier-Stokes equations provided an initial suggestion for a critical Reyn-





Turning on turbulence. (**A**) The different flow states in pipe flow can be distinguished by their Reynolds numbers (Re). Below Re_E = 81.5, all perturbations decay monotonically in energy (E). Spatially extended coherent states (ECS) appear above Re_{ECS} = 773. Experimentally, it is possible to induce transient localized turbulence above $Re_{EXP} \approx 1600$. Avila *et al*. show that a spatially intermittent but temporally persistent turbulence (PT) forms above Re_{PT} = 2040. At some higher but as yet undetermined Reynolds number, one may expect the flow to become spatially homogeneous. (**B**) Avila *et al*. could observe splitting of localized "puffs" of turbulence in numerical simulations when flow was suddenly increased so that Re jumped from 2200 to 2300. Fluid flow is from left to right. A puff stretches in the downstream direction (bottom frame), a new puff is created (middle frame), and once the puffs are sufficiently separated, they can stretch (top frame) and eventually break up again.

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olds number with the discovery of fully three-dimensional, spatially extended and persistent flow structures (*5*, *6*)—coherent structures—that were subsequently also identified in experiments (*7*). These structures appear at specific flow speeds that can be computed numerically with high precision and can provide a critical Reynolds number. However, we do not have any a priori information concerning where these critical points are and what the associated flows look like. At present, the lowest *Re* where some structures have been found is 773 (*8*).

The presence of many coherent structures of different shapes suggested that they provide a scaffold that could support turbulent dynamics by creating a multitude of connections between these states (*2*). For low Reynolds numbers, it was accepted that the tangle of connections was not woven with sufficient tightness to capture the turbulent dynamics forever. It was expected that at higher Reynolds numbers exceeding a critical value, the turbulence would become persistent (*9*), but more extensive experimental and numerical studies contradicted the initial agreement: The lifetimes increased rapidly, but there was no finite number at which they would diverge (*10*). Accordingly, the critical Reynolds number would be infinity, and all turbulence in pipe flow would be transient, albeit with excessively long lifetimes.

Avila *et al*. resolved this puzzling behavior and identified the missing feature that had not received sufficient attention: Turbulence in pipe flow has the unusual property that for Reynolds numbers below about 2300, it remains localized in short "puffs" that move downstream without much change in form. Because of their finite lifetime, the puffs should disappear one by one, and only the laminar profile would remain at long times. However, Nishi *et al*. (*11*) showed that puffs can split. In one process, fluctuations in the middle of the puff may become strong enough to introduce a laminar region that then pushes the two elements apart (see the figure, panel B, for an example from a numerical simulation). In another case, patches of turbulence swept downstream in the center of the fluid may attach to the walls and start new turbulent puffs. Such processes introduce connections between the puffs so that they can no longer be considered in isolation. In particular, if a puff manages to split before it decays, the sibling may carry on the turbulence, spatial and temporal couplings become important (*12*), and there may always be some turbulence somewhere along the pipe.

Avila *et al*. compared the lifetime of puffs with the time it takes for them to split. They overcame the difficulty of inducing turbulence at these low Reynolds numbers by creating a stepwise perturbation—they injected a water jet into the flow to create puffs of turbulence. With increasing Reynolds number, the lifetimes of puffs increased rapidly and the time to split decreased. In the critical region where these two times were similar, only one splitting or decay event occurred for every 10,000 injections of the jet. Such rare events are inaccessible in numerical simulations. Avila *et al*. provide convincing evidence for a crossing of the two curves at *Re* = 2040. On the basis of previous studies (*12*, *13*), a higher value might be expected, but the difference presumably comes from a poorer statistical method that missed the important rare events.

The findings of Avila *et al*., and even more so their method of analysis, bring into focus the spatiotemporal aspects of the transition problem (*14*). They pave the way for a better understanding of the transition in pipe flows and related shear flows, such as plane Couette flows and perhaps even boundary-layer flows, and connect the transition to the spatial intermittency and phase transitions in directed percolation (*15*). They provide not only the long-sought critical Reynolds number for pipe flow, but also define a critical change in our approach to studying turbulence transitions in spatially extended systems.

References

1. P. Drazin, W. Reid, *Hydrodynamic Stability* (Cambridge Univ. Press, Cambridge, 2004).
2. B. Eckhardt, *Philos. Trans. R. Soc. London Ser. A* **367**, 449 (2009).
3. K. Avila *et al*., *Science* **333**, 192 (2011).
4. A. Meseguer, L. Trefethen, *J. Comput. Phys.* **186**, 178 (2003).
5. H. Faisst, B. Eckhardt, *Phys. Rev. Lett.* **91**, 224502 (2003).
6. H. Wedin, R. R. Kerswell, *J. Fluid Mech.* **508**, 333 (2004).
7. B. Hof *et al*., *Science* **305**, 1594 (2004).
8. C. C. T. Pringle, R. R. Kerswell, *Phys. Rev. Lett.* **99**, 074502 (2007).
9. H. Faisst, B. Eckhardt, *J. Fluid Mech.* **504**, 343 (2004).
10. B. Hof, J. Westerweel, T. M. Schneider, B. Eckhardt, *Nature* **443**, 59 (2006).
11. M. Nishi, B. Ünsal, F. Durst, G. Biswas, *J. Fluid Mech.* **614**, 425 (2008).
12. D. Moxey, D. Barkley, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 8091 (2010).
13. J. Rotta, *Ing. Archiv* **24**, 258 (1956).
14. P. Manneville, *Phys. Rev. E.* **79**, 025301 (2009).
15. H. Hinrichsen, *Adv. Phys.* **49**, 815 (2000).

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EVOLUTION

Sex, Death, and the Red Queen

Michael A. Brockhurst

Experiments involving host-parasite interactions demonstrate the evolutionary benefits of sexual reproduction.

Sex is hard to explain. Since males can't reproduce by themselves and often contribute nothing except genes to offspring, a population of asexual females can grow at double the rate of a population that reproduces sexually (*1*). Why then, given this "cost of males," do most plants and animals indulge in biparental sex? One possible solution is that sex accelerates adaptation; the Red Queen hypothesis, for example, proposes that sex gives plants and animals an edge in the never-ending battle against their coevolving parasites (*2*–*4*). Although researchers have collected empirical field data consistent with the Red Queen hypothesis from a range of natural host-parasite systems, direct experimental evidence that coevolving parasites select for sex in their hosts has proven elusive. On page 216 of this issue, Morran *et al*. (*5*) pin down some of that direct evidence. In laboratory experiments, they grew several populations of nematode worms, some with and some without a bacterial parasite, to provide the most definitive support yet for the Red Queen's answer to why sex evolved.

As first conceived in 1973 by evolutionary biologist Leigh Van Valen, the Red Queen hypothesis had little to do with sex. Van Valen used the Red Queen's race, from Lewis Carroll's *Through the Looking-Glass*, as an analogy for nature (*6*). In Carroll's story, Alice and the Red Queen run as fast as they can but never get anywhere (*7*). In Van Valen's view of nature, species continually evolve but their fitness never increases because each adaptation is countered by adaptations by their competitors and enemies (*6*). He suggested that this coevolutionary mechanism could explain why rates of extinction within animal groups remain near constant through geological time. Biologists later co-opted the Red Queen analogy into a new coevolutionary hypothesis for the evolution of sex (*4*). Mathemati-

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