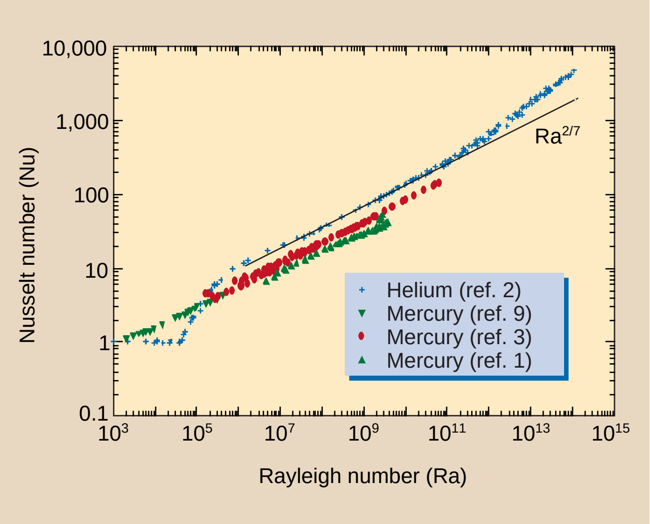

Figure 1 **Dimensionless heat flux (Nu) versus temperature difference (Ra) in Rayleigh–Bénard convection. In mercury ($Pr = 0.025$), data from three experiments agree with the $Nu \propto Ra^{2/7}$ law[1,3,9]. In helium ($Pr \approx 1$) the data[2] indicate an increase in Nu, and possibly a trend towards an ultimate regime, $Nu \propto Ra^{1/2}$. Although Ra is smaller in mercury than in helium, the corresponding Reynolds numbers are comparable.**

physical constants, covering a range of Ra, in the same experimental cell. Experiments performed in Chicago[7] in turn confirmed this result, and produced yet other scaling exponents, involving local temperature fluctuations. A regime of 'hard turbulence' was defined, as opposed to the smoother fluctuations obtained at lower Ra, but this is just the kind of turbulence observed in a saucepan. The Chicago group proposed a model, using scaling estimates for plume velocities and matching with the bulk flow, to provide a good agreement with the measured exponents. The Nu versus Ra exponent was identified as $\gamma = 2/7 = 0.285$.

In principle, this model cannot be extrapolated to the limit of very high Rayleigh numbers. It relies on an assumption that the thermal boundary layer is thinner than the viscous boundary layer, which does not hold in this limit[8]. New regimes, possibly the ultimate turbulence $Ra^{1/2}$, are then expected at higher Ra. Glazier *et al.*[3] have clearly reached regimes with thermal boundary layer exceeding the viscous one, but they still find a good fit with the 2/7 law, without any evidence for changes in the heat flux or turbulence structure. They conclude that the expected ultimate regime may be a chimaera.

This work contradicts earlier claims of a transition obtained in mercury[1] (but the limited range of Ra did not allow a firm conclusion). It is also at odds with results in helium gas[2], but not directly so because the Prandtl number is different (Fig. 1). There is some discrepancy between the new data with helium[2], and older experiments[7] (which were more limited in Ra), so the transition may be sensitive to the experimental conditions. A high sensitivity to initial perturbations is observed in transition to turbulence of ordinary boundary layers, for instance in the historical experiment with pipes performed by Reynolds himself, and a similar behaviour could occur for the onset of shear-driven turbulence in the convective boundary layers.

Clearly, further experiments are needed to settle this issue — it is a question of fundamental interest that challenges our understanding of turbulence. It is also of practical use in some engineering problems, for instance when using heat extraction by natural convection for a safer design of nuclear power plants. Extrapolating the scale of a model may be wrong if transitions to new regimes can occur. Finally, the weather system is a very complex case of natural convection. Here, ground topography or radiative effects probably dominate the boundary layers, so the $Ra^{1/2}$ regime would be expected, but it is difficult to test the absence of well-controlled flow conditions. It will be hard to fully trust a climate prediction as long as the simplest Rayleigh–Bénard convection remains out of reach of turbulence models.

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Fungal biology

Coming up for air and sporulation

Nicholas J. Talbot

Fungi are familiar to us as mushrooms that we can eat, toadstools that we shouldn't eat, and moulds on food that we have failed to eat. In each case, the visible fungus is composed of thread-like cells called hyphae, which either pack together to form mushroom fruit bodies or build up into a furry mycelium, or mould. In a paper in *Current Biology*[1], Wösten and colleagues reveal that proteins known as hydrophobins constitute the special ingredient that releases these fungal structures from their damp surroundings and enables them to grow up into the air to sporulate.

Fungi spend most of their lives encased in a wet environment such as wood, leaf litter or, in the case of pathogenic fungi, plant or animal tissue. Fungi proliferate by producing extensive hyphal networks that spread in all directions, secreting enzymes to degrade complex nutrients into simple sugars which are taken up to sustain the growing cells. To spread to new territory, however, most fungi need to grow into the air and produce spores. These spores are carried on upwardly projecting aerial hyphae or (in the case of sexual spores) in elaborate fruit bodies such as mushrooms and polypores. Wösten *et al.*[1] have shown that for a fungus to produce aerial structures, it must escape the surface tension of the water that normally surrounds it.

This process involves the action of a remarkable class of fungal proteins called hydrophobins. These are small proteins that are secreted in abundance by filamentous fungi[2]. They are very diverse in amino-acid sequence but they all have a set of eight cysteine residues and are predominantly hydrophobic in character. In spite of this diversity, even quite different hydrophobins are functionally interchangeable among species, suggesting that they share conserved physical characteristics[3]. The most extensively studied hydrophobin — and also the one investigated by Wösten *et al.* — is SC3, a hydrophobin produced by the gill-mushroom fungus *Schizophyllum commune* (Fig. 1)[2,4]. SC3 forms a water-repellent (hydrophobic) outer coating on aerial

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Figure 1 **Out in the open — the fruit bodies of *S. commune.***

hyphae of *S. commune*, which can be seen under the electron microscope as a layer of interwoven rodlets[4,5]. Targeted disruption of the *SC3* gene produces mutants (Δ*SC3*) that are unable to form aerial hyphae[6].

SC3 is secreted as a monomer, but when it encounters an air–water interface or an interface with a hydrophobic surface, it aggregates into a large polymeric complex[4]. This hydrophobin polymer forms a thin layer that is hydrophobic on the side where it is decorated with rodlets, and hydrophilic on the other. This alteration in structure of SC3 occurs in response to changing environmental conditions encountered by the fungus as it grows from water into the air, allowing the fungus to produce hydrophobic aerial hyphae.

But this is only half of the story. SC3 is produced abundantly by *S. commune* even when the fungus is growing in liquids[2,4] and the importance of this is now clear. In a simple experiment, Wösten *et al.* showed that the normal surface tension of water, 72 mJ m^{-2}, can be reduced to as low as 24 mJ m^{-2} by adding purified SC3. This makes SC3 the most powerful surface-active protein known and suggests that secretion of hydrophobins at high concentrations dramatically lowers the surface tension, allowing hyphae to escape the liquid and grow into the air. Consistent with this, the surface tension of a liquid culture of *S. commune* falls by a similar amount during growth of the fungus; and when purified SC3 is added to culture medium surrounding a Δ*SC3* mutant, the mutant becomes able to put out aerial hyphae.

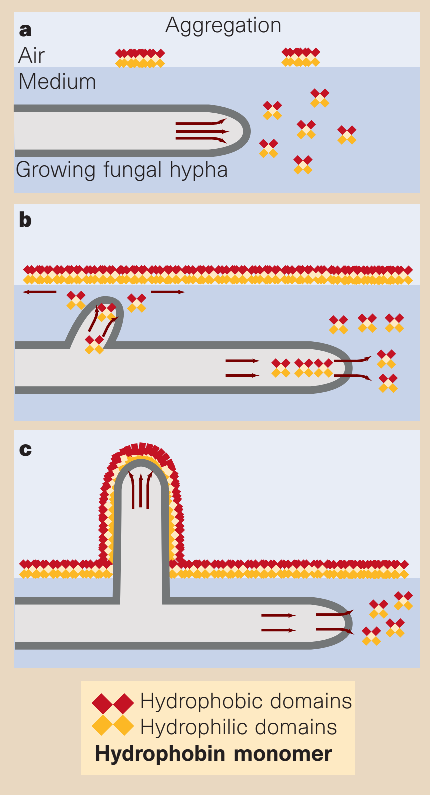

Figure 2 **Model for the emergence of aerial hyphae based on the experiments of Wösten *et al.*[1] with the gill mushroom *S. commune*.** a, **A hypha growing in its normal damp environment, surrounded by a film of water. During growth, SC3 hydrophobin is secreted in abundance. SC3 monomers are depicted as having two hydrophobic domains and two hydrophilic domains[2] and aggregate at the air–water interface into an amphipathic (with a hydrophobic and a hydrophilic face) layer.** b, **This causes a dramatic reduction in surface tension, allowing the hypha to escape and grow into the air. Hydrophobin secretion continues.** c, **The aerial hypha continues to secrete SC3 hydrophobin, which forms a hydrophobic rodlet layer on the outside of the cell wall.**

Aerial hyphae in Δ*SC3* mutants that have been treated with exogenous SC3 protein are hydrophilic, indicating that continued secretion of SC3 from aerial hyphae is required for the formation of a hydrophobic surface layer. Thus SC3 has two functions. First, it lowers the surface tension of the water that surrounds the hyphae, allowing them to emerge from the liquid; and second, it coats aerial hyphae with a hydrophobic wall that enables them to grow into the air (Fig. 2) and probably to withstand desiccation.

Since they were first identified in the early 1990s, hydrophobins have been found in many filamentous fungi and may well be ubiquitous[2]. Hydrophobin genes are absent, however, from the genome of the unicellular fungus *Saccharomyces cerevisiae*. The evolution of hydrophobins may therefore have been concurrent with the divergence of the filamentous fungi and, in particular, their colonization of terrestrial ecosystems.

There is still much to be learned about these unusual proteins. Certain fungal species, for example, produce a variety of hydrophobins with diverse biochemical properties[2], indicating that, in addition to their role in aerial growth, hydrophobins may participate in many other developmental processes. The structural biology of hydrophobins also remains largely unexplored. How, for example, do these small proteins aggregate in response to air–water interfaces, and what conformation do hydrophobin monomers adopt within a rodlet layer? Wösten *et al.* have reached an important milestone in showing how hydrophobins bring about aerial growth in fungi: now we need to determine the molecular basis of their activity. ☐

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Daedalus

Press-fit chemistry

Many catalysts provide a passive surface or cavity on which reacting molecules can sit in the right position to react together. Daedalus is now dreaming up a more active type of catalyst.

He recalls the catalytic zeolites, which are riddled with molecular-scale cavities, within which entering molecules can react. Sometimes the cavities actually expand when molecules enter them. So, says Daedalus, imagine an elastic porous catalyst, perhaps a piezoelectric zeolite or microporous silica, expanding and contracting under external control. In its expanded state, it allows reacting molecules to enter its cavities freely. Then it contracts, squashing them together in a way that forces them to react. On the next expansion, the product molecule can escape, to be replaced by new reagents. The cycle could be repeated at megahertz rates.

DREADCO chemists are now trying it. They are combining the skills of the piezoelectric quartz crystal and silica-based catalyst industries to study the effects of setting such catalysts into intense vibration. With luck, the chemical yields of standard test reactions should increase dramatically. Even better, a piezoelectric catalyst could be 'tuned' electronically by setting it into different vibrational modes. A mode which elongated its molecular sites or cavities would give linear molecules; one which flattened them would encourage planar ones. A single catalyst could generate a wide range of products under perfect control.

But the real goal of the project is to find entirely new reactions, yielding hitherto unknown products. Imagine, says Daedalus, a piezoelectric porous catalyst whose cavities can expand to accept three dinitrogen molecules arranged as a hexagon. When such a cavity contracts, the molecules will be squashed together to form the hitherto unknown hexagonal molecule N_6. Being isoelectronic with benzene, it could well be stable. On the next expansion, it would be released, and more dinitrogen taken up. O_6, tetrahedrane (dimerized from acetylene) and many other unknown molecules, could be made in the same way.

N_6 would probably be a powerful high explosive, O_6 a ferocious oxidizing agent, and tetrahedrane an energetic rocket fuel. But they are just the start of a new era of chemical synthesis. A whole bonanza of weird, warped, incredible molecules could pour from the new cornucopia of piezoelectric catalysis.

David Jones