rapidly identify and fight microbial pathogens, because many of these have become resistant to antibiotics. Fluid-filled cantilevers have previously been used[3] to weigh single living bacterial cells with sub-femtogram mass resolution (1 fg is 10^{-15} g), suggesting that this method could be used for detecting very low concentrations of pathogens. Moreover, cantilever technologies have been used to study the interaction of bacterial cell walls with the clinically valuable antibiotics vancomycin and oritavancin[7], providing insights into how these drugs work. Cantilevers have also allowed the sensitivity and resistance of bacteria to antibiotics to be measured in minutes, which is much faster than conventional culture methods[8]. Martínez-Martín and colleagues' cell balance therefore holds great promise for studying the mechanisms of action of antibiotics, and for identifying the most efficient antimicrobial therapies. ■

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In Retrospect

Twenty years of drying droplets

When a particle-laden droplet evaporates on a solid surface, the particles form a ring-like deposit. The explanation for this phenomenon, provided in 1997, has led to advances in many areas of science and engineering.

RONALD G. LARSON

Why does a drying droplet, such as a spilt drop of coffee, leave a circular ring as its residue, rather than a uniform spot? Twenty years ago this month, Deegan *et al.*[1] published a paper in *Nature* that explained this commonly observed phenomenon, which is known as the coffee-ring effect. Their results, and the broad interest in and applications of the effect, have spawned thousands of publications, and advances including potential improvements to ink-jet printing[2], methods of patterning surfaces[3] and techniques for disease detection[4].

Deegan and colleagues' explanation for the coffee-ring effect is surprisingly simple (Fig. 1). When a particle-laden droplet dries on a solid surface, the rate of evaporation is typically highest near the droplet's outer rim, known as the contact line. This line is usually pinned to the surface because of microscopic surface roughness, meaning that it must draw liquid from the droplet's interior to replace what is lost to evaporation. The particles in the droplet are thereby dragged to the contact line, where they form a ring that helps to maintain line pinning.

The authors' intriguing explanation, and their analysis of the associated deposition physics, have led to an outpouring of theoretical and experimental work, much of it extending well beyond the coffee-ring effect. For instance, drying conditions have been discovered that lead to deposits at the droplet centre rather than, or in addition to, the ring at the edge[5]. Conditions have also been found for deposition patterns that resemble the spokes of a wheel[6], snowflakes[7], webs[8], and cones that grow higher than the initial height of the droplet[9].

As observed and explained two years before the authors' study, concentric-ring deposits, rather than single rings, can be produced by stick–slip motion of the contact line[10], whereby the edge of the droplet and the solid surface alternate between sticking to each other and sliding over each other. In other cases, deposition initially occurs at the top of the droplet, along the liquid–air interface. As the droplet dries, the deposit is then brought to rest on the surface, giving rise to other types of distinctive pattern. Finally, when particles make up a large fraction (more than 10%) of the droplet's volume, deposits can resemble structures ranging from volcanoes[11] to arches[12], depending on the drying conditions. It is amazing that such a huge range of patterns can be generated by simply spotting a droplet onto a surface and letting it dry.

Following Deegan and colleagues' work, it was shown that deposition can be steered by more than just evaporation and contact-line pinning. For example, it can be redirected by a type of mass transfer called Marangoni secondary flow[5], which is responsible for producing 'tears of wine' — the ring of liquid that forms near the top of a wine glass, from which droplets constantly form and trickle back into the wine. Depending on the type of material suspended in the droplet, deposition can also be influenced by crystallization dynamics, and the jamming of particles or buckling of

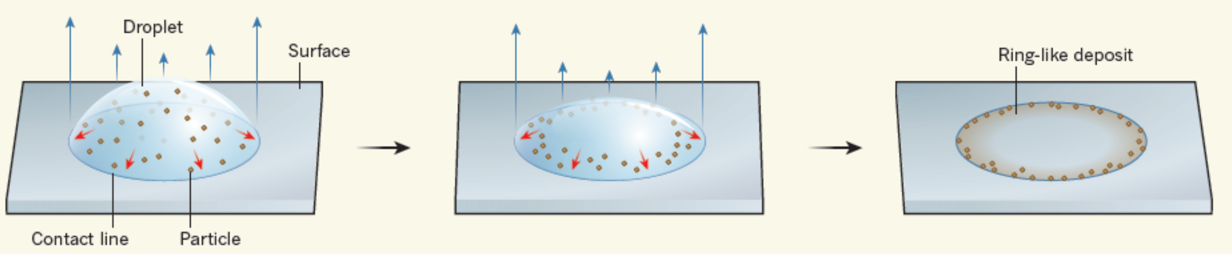

Figure 1 | The coffee-ring effect. In 1997, Deegan *et al.*[1] reported an explanation for the coffee-ring effect — the observation that a particle-laden droplet, such as a spilt drop of coffee, leaves a ring-like deposit when it dries on a solid surface, rather than a uniform spot. The rate at which such a droplet evaporates (blue arrows) is typically highest near its outer rim, known as the contact line. This line is usually pinned to the surface as a result of microscopic surface roughness, and so it must draw liquid from the droplet's interior (red arrows) to replace what it loses to evaporation. The particles in the droplet are thereby dragged to the contact line and, when the droplet has fully evaporated, they form a ring-like deposit. The authors' explanation for this effect has led to improvements in, for example, ink-jet printing[2] and the patterning of surfaces[3].

particle films at the liquid–air interface[13].

Drying droplets are of interest not only for their deposition patterns, but also for their transport properties. The fluid in a drying droplet exhibits all three classical forms of transport: it transfers mass, momentum and heat, the last of these because evaporation causes the droplet to cool. Deegan *et al.* were able to describe the first two of these forms of transport in their droplets using relatively simple equations. In other cases, the transport equations are coupled, and lead to complex deposition patterns and unstable flows of material that are usually studied only in large-scale experiments. In addition to transport phenomena, possible features present in a drying droplet include contact-line de-pinning and re-pinning, and friction between the suspended particles and the solid surface.

The range of materials that have been dried on a surface is vast. Liquids containing suspended particles that have shapes ranging from spherical to elongated, as well as nanoparticles, salts, polymers, DNA and proteins have been deposited in patterns that are complex, yet reproducible[3]. A drying droplet is therefore a small, simple and inexpensive platform on which multiple phenomena common to manufacturing and industrial processing can be studied and thoroughly understood.

In the past decade, practical applications of the work by Deegan *et al.* and others have extended in many directions. For instance, ink-jet and some other forms of printing require that a drying solvent leaves a deposit of ink. This process is shaped by the physics of drying, for which better control than is currently possible is desired[2]. Additionally, proteins dried on a surface leave a pattern distinctive of that protein, opening up the possibility of simple, low-cost detection of protein or other disease markers in blood or saliva[4,14].

More than 300 years ago, the Dutch microscopist Antonie van Leeuwenhoek discovered a world of microorganisms when he peered through a microscope into a tiny liquid droplet. In modern times, a world of physical chemistry can similarly be observed by watching a droplet dry — as Deegan *et al.* did. ■

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50 Years Ago

The total emission of smoke in Britain … has been declining for some years but reaches a higher concentration in winter. Deposited matter, including soot, tar, dust, grit and ash, is mainly derived from the combustion of solid fuels. So, too, is sulphur dioxide; in 1963, 68 per cent of sulphur dioxide came from burning coal, 7 per cent from coke and 25 per cent from oil. At Battersea and Bankside power stations in London, flue gases are washed with water from the Thames to which chalk has been added: this process removes 90 to 98 per cent of gases but it is costly … Fluorides are emitted by some brickworks and possibly by some potteries and cement kilns, but fluoride pollution is rarely reported in Britain now. It remains to be seen whether photochemical or oxidant smog, often referred to as Los Angeles smog, will be troublesome in Britain in future.
From *Nature* 28 October 1967

100 Years Ago

In general, in normal times it is perhaps no exaggeration to say that neither the average individual nor the average nation approaches within 50 per cent. of their possibilities. Nothing short of a war threatening the national existence can shake a nation out of its lethargy. Similarly, the average individual cannot be induced to put forth his best efforts without the strongest of incentives. It is unfortunate that this is the case. However, with sufficient attention given to the problem by trained experts in mental science, it is quite possible that at some future date as high as 60 or 80 per cent. of the possibilities may be realised without any appeal to arms for the nation or any unusual incentive for the individual.
From *Nature* 25 October 1917

PHOTOBIOLOGY

How flowers get the blues to lure bees

The petals of a range of flowers harbour repeated patterns of nanostructures that show similar levels of disorder across species. This degree of disorder produces a blue halo of scattered light that helps bees to find flowers. SEE ARTICLE P.469

DIMITRI D. DEHEYN

The ability to effectively pass genetic material to a sexual partner is a powerful driver of evolution. Humans and other mobile organisms have evolved so that sexual partners are attracted to one another. But immobile organisms such as plants must rely on an intermediary carrier — bees carrying genetic material in pollen, for instance. These carriers are crucial to the survival of immobile species, and have co-evolved closely with them[1,2]. Moyroud *et al.*[3] report on page 469 that diverse flowering plants have evolved to produce a 'blue halo' of colour that attracts bumblebees (*Bombus terrestris*).

Pollinators use a combination of olfactory and visual cues to find flowers[4,5]. For bees, the colours and shapes of flowers are probably the dominant discriminatory factors. However, the idea that bees can see colours has been challenged by studies[6,7] of photoreception and spectral sensitivity, which showed that bee eyes are relatively insensitive to most colours, except blue.

Colour commonly originates from pigment