Biodiversity

Bacterial game dynamics

Martin A. Nowak and Karl Sigmund

Studies of three bacterial strains engaged in an interaction that mimics the game 'rock–paper–scissors' show the importance of localized interactions in maintaining biodiversity.

It is not surprising that games as absorbing as bridge and chess have their world federations and international unions. But not everyone knows that even a game as lowly as rock–paper–scissors has its own society. This game, which must surely be very old, can be explained to any toddler. Two players signal, on a given cue, either rock (fist), paper (flat hand) or scissors (two fingers). If I display a flat hand and you show me your fist, I win, as 'paper wraps rock'. Similarly, scissors cuts paper, and rock smashes scissors. If both players make the same signal, the game ends in a draw. And in case you think of it as a rather simple-minded pastime, you should take a look at the home page of the World RPS Society[1], which is a treat. Among other features there are links to learned papers, although you are advised not to visit the links in the probabilistic section, filled as it is with "pseudo-scholastics". No such ban appears against the link to a paper in *Nature* describing three mating strategies of the male lizard *Uta stansburiana*[2]. And now *Nature* should hit the website again, with the report by Kerr and colleagues on page 171 of this issue[3].

Kerr *et al.*[3] set out to investigate the mechanisms that maintain biodiversity in ecosystems, by studying several diverse strains of *Escherichia coli* bacteria. These strains can produce a toxin, or not; and they can be resistant to the toxin, or not. We may assume that the bacterial devices for producing both the toxin and the 'antidote' that confers resistance are costly in the sense that they require resources that could otherwise have been used by the bacteria to multiply faster.

There are four potential strains. The one producing the toxin but not the antidote effectively commits suicide. This strain is a non-starter, and we may ignore it (as did Kerr *et al.*). The other three are engaged in a rock–paper–scissors type of competition. The poison- and antidote-producing strain kills that which produces neither poison nor antidote. The strain that produces the antidote but not the poison outgrows the one that produces both, by economizing on the cost of an ineffective poison. And in the absence of the toxin-producing strain, the strain that produces no antidote outgrows the antidote-producing type, which is paying for an unneeded device.

These two-way bacterial interactions have been described previously. And similar rock–paper–scissors cycles of spiteful measures and costly countermeasures occur in other evolutionary contexts, for instance in the genetics of sexual species. Some chromosomes acquire mutations that prevent their opposite number (inherited from the other parent) from making their way into eggs or sperm, and so to the next generation. Some of these mechanisms for subverting the fair segregation of chromosomes act like the bacteria, by means of a poison-and-antidote-type principle[4].

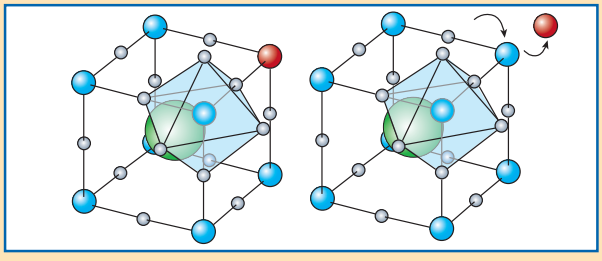
But what happens when the three *E. coli* strains are all in the same environment? The mere knowledge that the outcomes of pair-wise competition form a rock–paper–scissors cycle is not enough to predict what happens when all three types are present[5,6]. The three competitors might co-exist permanently; this seems to apply, for instance, to the male lizards that have three different mating strategies[2]. Or one type might be ousted, and a second type outcompeted by the third, leading to just one survivor. Kerr *et al.* find that this latter outcome holds for our bacteria. If all three strains are equally

Chemistry

Cleaning up catalysts

Since its introduction more than 20 years ago, the catalytic converter has sharply reduced automotive emissions. Using catalysts containing palladium, platinum and rhodium, a converter breaks down harmful carbon monoxide, nitrogen oxides and hydrocarbons before the exhaust leaves the car's tailpipe. But these precious metals are expensive and are produced through the intensive and polluting chemical processing of sulphide ores extracted from often treacherous underground mines.

On page 164 of this issue, Yasuo Nishihata *et al.* (*Nature* **418,** 164–167; 2002) propose a new catalyst for automotive-emissions control that lasts longer and accomplishes its task more effectively than conventional catalysts. The material, a perovskite containing small amounts of palladium (Pd), could reduce by 70–90% the amount of precious metals needed to meet today's car emission standards.



Catalytic converters consist of a highly porous ceramic structure coated with finely divided catalytic material. To ensure immediate action when the car is started, converters are placed close to the hottest part of the car, the engine. Over time, heat exposure causes the tiny particles of precious metal to agglomerate, thus reducing the catalyst's overall surface area and hence its activity. To counter this effect, conventional catalytic converters are loaded with an excess of precious metal, ensuring that performance targets are met for vehicle use over the expected range, usually 80,000 km.

Nishihata *et al.* demonstrate that excess-metal loading is not needed if the perovskite $LaFe_{0.57}Co_{0.38}Pd_{0.05}O_3$ is used as the catalyst. This material, first investigated for catalytic-converter applications in the 1970s, maintained its high metal dispersion and high catalytic activity during a 100-hour test in engine exhaust. In the same test, the activity of a conventional catalyst (alumina impregnated with palladium) decreased by 10%.

The resilience against metal-particle agglomeration results from the perovskite's ability to respond structurally to the fluctuations in exhaust-gas composition that occur in modern petrol engines. These fluctuations switch the exhaust environment continuously from an oxidizing to a reducing atmosphere. In separate tests, the authors established that Pd is firmly incorporated into the perovskite lattice of the oxidized $LaFe_{0.57}Co_{0.38}Pd_{0.05}O_3$ catalyst (see figure, left). But the Pd atom (red) moves out of the structure, being replaced by an iron atom (blue), in the reduced material (see figure, right). It is this fully reversible hopping of Pd into and out of the perovskite structure that seems to suppress the agglomeration of the metal and thus the slow deactivation of the catalyst.

Although catalytic converters have already made a significant contribution to emissions control, Nishihata *et al.* show that more can still be done to address the environmental impact of car use.

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frequent at first, the type producing antidote but no poison eliminates the others.

Kerr *et al.* also show, however, that this loss of diversity occurs only if the bacterial populations are well mixed. Otherwise, all three strains survive. This conclusion has been predicted on paper: a rush of theoretical investigations during the past decade has shown, in great generality, that if dispersal of a population is limited and its interactions with other populations are localized, then diversity is protected to a large degree[7,8]. This holds for an astonishing variety of scenarios, for instance in epidemiological models, community ecology, plant genetics, animal behaviour, molecular evolution[9] and game theory[10]. Such spatial models are usually much harder to analyse than their homogenized 'mean field' counterparts. But computer simulations warn us that, in many cases, 'mean field' can lead to wrong conclusions.

And Kerr and colleagues are not the first to show that localized interactions of the rock–paper–scissors type can turn a 'one winner' outcome into a dynamic coexistence of all three types, endlessly chasing each other across the board[11]. The beauty of their paper is that they show this not only on a computer screen, but also in 'real life'. To set up the well-mixed case, the authors put all three strains in a flask, shake this cocktail, transfer a few drops to another flask, shake it again, and so on. Soon the flasks contain only the resistant, non-toxic strain. To ensure localized interactions, on the other hand, Kerr *et al.* spread the strains on a plate to let them grow, then press a cloth on the plate, transfer whatever clings to the cloth onto another plate, and so on. All three strains survive, with the boundaries between them shifting to and fro, reflecting the cyclic invasion and displacement of one strain by the next. So the outcomes on the plate and in the flask are strikingly different.

This approach opens new vistas for understanding how biological communities are built up — one of the most intriguing aspects of the study of biodiversity. The results of sequential invasions and extinctions of species can create complex links and webs in an ecosystem, not least because the outcome of an invasion depends so much on its timing and other contingencies. Large-scale experiments in community construction are generally hard to come by — not often do volcanic rocks emerge, providing barren ground for colonization. So ecologists have increasingly turned, since G. F. Gause's work in the 1930s, to manipulating mini-worlds inhabited by microbial species[12]. The paper by Kerr *et al.* gives a new impetus to such investigations, by stressing the importance of the geometry of neighbourhoods. Many habitats resemble the surface of a pizza more than a well-stirred bowl of soup. ■

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Apoptosis

Repulsive encounters

Giovanna Chimini

In multicellular organisms, cells are often required to die. They are then eaten by 'phagocytic' cells. But how do the phagocytes distinguish between dead and living prey? New work provides an unexpected answer.

Making decisions on the basis of social cues is an everyday challenge for human beings — and for our cells. On page 200 of this issue, for instance, Brown and colleagues[1] describe how predatory immune cells decide whether or not to eat other cells on the basis of a molecular 'handshake'.

This decision is made in the context of the programmed deletion of cells, or 'apoptosis', that is an essential feature of embryonic development, tissue organization and cell turnover in multicellular organisms[2,3]. The programme basically consists of two tightly coupled events, the death of cells and their burial — or rather, their consumption by the body's professional predators, immune cells known as phagocytes. Three keywords govern the burial rite[4]: swiftness, because no cellular corpses are allowed to linger around; efficiency, because the day-to-day burden of dead cells is enormous; and discretion, to protect the surrounding environment from harm. But between death and burial lies decision-making: how do phagocytes discriminate between dead or dying cells and their healthy neighbours?

It is generally accepted that the onset of the death programme makes cells appetizing because it exposes attractive 'eat me' signals[5]. These involve changes in the cell surface, which can be tracked experimentally by the

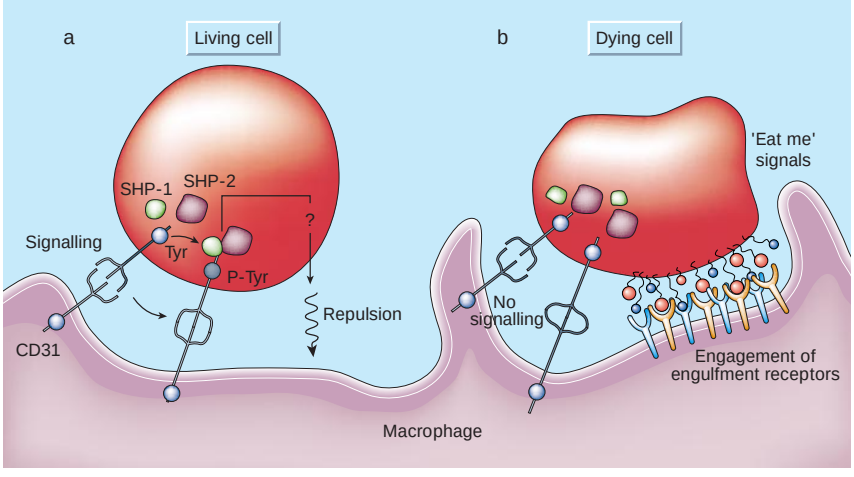

Figure 1 **To eat or not to eat? In vertebrates, predatory macrophage cells continuously meet potential 'prey' and make contact with them through their respective CD31 proteins.** a, **When the target cells are healthy and viable, 'outside-in' signalling is triggered, probably involving the modification of tyrosine amino acids in the intracellular tail of CD31 with phosphate (P-Tyr), and interaction with the proteins SHP-1 and SHP-2. This results in 'inside-out' signalling, repelling the macrophage.** b, **When the target cells are dead or dying, outside-in signalling through CD31 is disabled and the interaction with the macrophage persists. This assists definitive recognition of the dying prey by specialized engulfment receptors on the macrophage.**