galaxy groups. This is not easy, because their X-ray emission is weaker than that of large clusters. Second, reheating from star formation may not be the whole story. Bright galaxies are found at the centre of many clusters, and it is now widely believed that these harbour central black holes. Gas cooling onto these galaxies may serve to fuel the black hole, and it is possible that this, rather than supernova explosions, serves to reheat the low-entropy gas[9,10].

Solutions to these problems may soon be provided by the new generation of X-ray observatories now in operation in space. XMM-Newton is sensitive enough to measure the amount of gas in galaxy groups, whereas Chandra has the spatial resolution to study the interaction between central active galaxies and the gas surrounding them. These observational advances can be expected to stimulate further theoretical developments over the next few years. ■

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Evolution

Tides of tolerance

Karl Sigmund and Martin A. Nowak

Humans, and many other species, have a tendency to cooperate and help each other. But how does such behaviour evolve? Some new computer simulations provide a plausible answer.

When Charles Darwin[1] published his theory of evolution in 1859, he knew that cooperation and altruistic behaviour present something of a problem for a concept that is based on competition and the struggle for existence. He did, however, anticipate a solution that was provided by William Hamilton[2] more than a century later: cooperation can emerge as a result of 'kin selection' in cases where interacting individuals are genetically related. On page 441 of this issue, Riolo and colleagues[3] discuss a new model for the evolution of cooperation, in which individuals help others that are, in some way, like themselves.

This is not the first time that the idea of 'like helping like' has been suggested as a route to the evolution of cooperation. Twenty-five years ago, Dawkins[4] introduced the 'green beard effect' as a thought experiment in sociobiology. Consider a gene that confers on its bearer not only a green beard (or any other distinctive label), but also the instinct to provide assistance to all other owners of a green beard. Individuals with such a gene would effectively form a self-serving clique, and so the gene would spread within the population.

Today, the green beard is a cherished icon of the 'selfish gene' view of natural selection, and similar effects have actually been found in nature[5]. But it still takes some effort to accept the idea of a gene producing, simultaneously, a signal and a predilection for the signaller. Such a double-effect gene seems contrived. Riolo *et al.*[3] discuss a more plausible model for the evolution of cooperation: individuals just need to like their like, something that most of us can relate to.

In traditional models of how cooperation can emerge[6], the evolutionary development of a fictitious population of 'agents' is simulated, on a computer, over many generations, with pairs of individuals meeting randomly as potential givers and receivers of help. Giving help entails some cost to the donor, and getting help provides a larger benefit to the recipient. Cost and benefit are measured in reproductive success, and offspring are supposed to inherit the parent's behaviour, unless mutations occur. Because 'selfish' individuals, who refrain from helping, incur no costs, they spread, and after some generations cooperation will be eliminated. But if individuals can guess whether recipients are likely to give assistance in their turn, they can channel help towards those who help, and discriminate against exploiters. In this way cooperation, based on reciprocation, can emerge[6].

Riolo *et al.*'s model[3] follows a similar pattern, but with some crucial differences. Each individual has a trait (or 'tag', as Riolo *et al.* call it), and is endowed with a tolerance level. Donors refuse to offer help if the trait of the recipient differs from their own by more than the donor's tolerance level. In other words, zero tolerance means that an individual helps only those who are exactly like it; maximum tolerance means helping everyone. Both the trait and the tolerance level are inherited by the offspring, with some mutations occasionally introducing new variations into the population.

The basic outcome of the computer simulations[3] is that a substantial degree of cooperation is established. Essentially, a 'dominant cluster' emerges, consisting of players sufficiently similar to help each other. This occurs even in the absence of repeated interactions and reputation effects — that is, without direct or indirect reciprocation. All that is needed is some recognition of what is 'similar', an ability that is widespread among animals[7] (odours or visual cues can provide the required information). So, the mechanism that leads to cooperation is a form of kin selection — either classical (if traits are inherited genetically) or social (if they are inherited culturally, like a dress code).

One attractive feature of the new simulations is the evolution of tolerance — the recognition mechanism that discriminates 'us' from 'them'. This tolerance does not freeze at some fixed value. Cyclically, it slowly increases over time, and then sharply declines. This drop occurs when the dominant cluster is dissolved from within as a result of mutation, by new individuals whose traits lie in the range of the dominant cluster but whose tolerance is considerably reduced. These newcomers are helped by all the residents of the established cluster but themselves help just a few, so they bear fewer costs than the established residents. A wave of intolerance then sweeps through the population, and in its wake a reduction in overall cooperation. But once a new dominant cluster is established, cooperation resumes at its former level and tolerance starts spreading again. The slow upward drift of tolerance seems to be due to a combination of mutational pressure and kin selection. It will be important in the future to explore the robustness of this phenomenon.

These oscillations of tolerance levels are striking, and bring to mind many historical instances. We are witnessing a wave of social and religious intolerance right now. It would be foolish, of course, to reduce the complexities of political life to the vagaries of a virtual population. Yet these computer simulations do capture the imagination, and may well lead to a cottage industry of follow-up investigations, just like Axelrod's famous computer tournaments based on the 'prisoners' dilemma' game[8].

The new scenario applies to both genetic and cultural tags[9]. Part of its appeal is its obvious link to reality — school ties, club memberships, tribal customs or religious creeds are all tags that induce cooperation. Some of these tags are easy to fake and might invite exploitation. Language, on the other hand, could be a reliable tag that is hard to fake; hiding one's accent in a foreign language is nearly impossible.

Furthermore, tags can help to encourage the usual suspects behind cooperation among unrelated individuals: direct and indirect reciprocation (whereby recipients of help return the help, either to the donor or to a third party). In other words, tags bolster the emergence of cooperation in repeated interactions, and might even promote long-term pairings based on similarity[10]. Indeed, to find out how much one has in common is one of the first delights of falling in love and contemplating a lifelong partnership.

But tags can also present major obstacles in overcoming segregation. Although the simulations by Riolo *et al.*[3] do not produce dominant clusters that split into rival tribes, any territorial distribution would favour such 'speciation'. Tags would then act as self-enforcing stereotypes, making it hard for tolerance to cross the divide. We know that discrimination is needed to sustain cooperation in the face of exploiters. But tag-based intolerance could turn discrimination away from the 'bad guys' and raise senseless antagonism. ■

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Surface chemistry

Catalysis frozen in time

J. K. Nørskov

Modern microscopes are not just for imaging. In the right hands they can be used to follow and control catalytic reactions on a metal surface — one atom at a time.

Solid surfaces act as catalysts for a large number of reactions: it is estimated that 20–30% of the gross national product in developed countries is dependent one way or another on this sort of catalysis[1]. The surface acts by adsorbing the reactants and encouraging them to react until the products leave the surface. Yet despite its importance, many aspects of catalysis by solid surfaces are not understood. The use of powerful tools is now helping to change that. Writing in *Physical Review Letters*, Hahn and Ho[2] show that they can manipulate individual atoms and molecules adsorbed on a metal surface to induce a catalytic reaction. By using this technique at low temperatures they can control the speed of the reaction, so they can follow important steps as they happen, atom by atom.

The catalytic oxidation of carbon monoxide (CO) is one of the simplest catalytic reactions, and is an important part of the reactions that take place in the catalytic converter in your car. In this context, CO is transformed into carbon dioxide (CO_2) by reacting with oxygen or nitrous oxide (NO) on the surface of a platinum, palladium or platinum–rhenium catalyst[3]. The reaction involves five steps, which are summarized in Fig. 1. At the low temperatures (13–45 K) used by Hahn and Ho, the two first steps (Fig. 1a) can occur on a silver surface, but the rest of the reaction requires higher temperatures to proceed spontaneously.

At these low temperatures the authors use a scanning tunnelling microscope (STM) to make the reaction happen and to image and manipulate the atoms and molecules on the surface (Fig. 1). An STM works by applying a voltage to a sharp metallic 'tip', which is scanned across the surface, and then recording the flow of electrons that tunnel between the surface and the tip. In practice, the flow of electrons is kept constant by adjusting the distance between the tip and the surface. When the tip is scanned over the entire surface, a record of its height at each point provides a detailed map of the surface at atomic resolution[4]. The STM can also be used to physically modify the surface: the electrons transferred from or to the tip can start a chemical reaction, or make atoms or molecules move on the surface[5,6]. Pushing or pulling an individual atom or molecule with the tip can also make it move.

Hahn and Ho use the STM to dissociate the oxygen molecules (Fig. 1b), to move individual CO molecules close to the oxygen atoms on the surface, and to induce the final reaction and desorption of the product (Fig. 1c, d). Along the way, they image the intermediates on the surface — they observe, for instance, a complex consisting of two oxygen atoms close to each other and to a CO molecule. They also used the STM in its 'inelastic electron tunnelling spectroscopy' mode to monitor the vibrational behaviour of CO as it is nudged closer and closer to the two oxygen atoms. The formation of the O–CO–O complex is confirmed by observing a change in the vibrational frequency of the CO. Measuring the spatial distribution of the vibrational intensity of CO within the complex provides information about the structure of the reactants. In a separate set of experiments they induced the reaction by first transferring the CO molecule to the tip (by using a voltage pulse), moving the tip into position over an adsorbed oxygen atom, and applying a new voltage pulse with the opposite sign to transfer the molecule back to the surface and to kick start the reaction.

These experiments provide atomic-scale details of a chemical reaction occurring at a surface. Intermediates that would not have a measurable lifetime at higher temperatures, and so cannot be observed during a thermal reaction, can be viewed directly. The clever part is to work at temperatures low enough for the intermediates to be frozen in time and to use electron injection rather than thermal excitations to make the reaction proceed.

The work of Hahn and Ho shows that it is possible to induce reactions that won't proceed thermally by using tunnelling electrons to activate the reaction. Using an STM tip to induce chemical reactions at a catalytic surface is not an efficient way of producing large amounts of chemicals, but it is analogous to the way natural catalysts (enzymes) manage

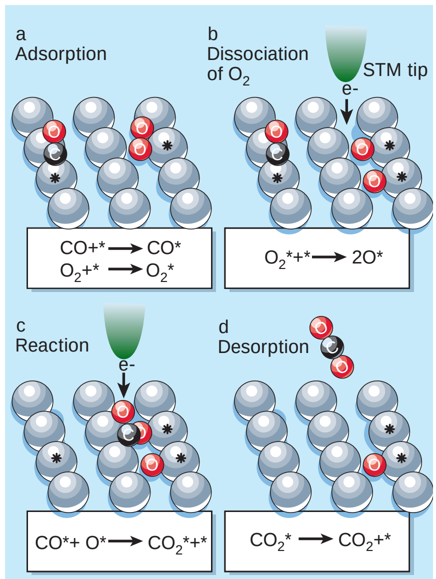

Figure 1 **Surface chemistry in action. The formation of carbon dioxide (CO_2) by catalytic oxidation of carbon monoxide (CO) on a metal surface is an important reaction in air purification, emission control and chemical sensing. In their experiment[2], Hahn and Ho show that CO and oxygen atoms (O) adsorbed on a silver surface can be transformed into CO_2 with the help of an STM tip, which transfers electrons to the reactants. With this technique the reaction can proceed at temperatures so low that every step of the reaction (a–d) can be watched closely. (An asterisk denotes a site on the surface that can form a bond to an adsorbed atom or molecule.)**