decoherence), in the same way as opening the box reveals the dead or alive cat.

In contrast, entangling states of many subsystems turns out to be a useful tool for quantum information processing. It has been shown that, by coherent manipulation of quantum states, quantum computers could solve certain problems much faster than conventional (classical) computers. This speed increase is directly linked to the fact that the register of a quantum computer can be prepared in a superposition of states, which are then processed in parallel. The creation of a 'universal' quantum computer becomes possible only if one can routinely prepare and handle entangled particles to serve as the storage sites of the quantum information. Moreover, the sensitivity of the entangled states (in particular, the large state prepared by Sackett et al.) with respect to interactions makes them a unique measuring tool. For example, we would like to measure the decoherence processes that cause errors in a quantum computation.

This is precisely why the new method for entangling many subsystems is an important step for the emerging field of quantum information processing. Sackett et al.[1] demonstrate for the first time an entanglement technique based on the ideas of Mølmer and Sørensen[10,11] that is applicable to any number of particles. In addition, this technique makes it possible to create maximally entangled states in a single step and on demand. Other entanglement experiments have relied on selection of suitable outcomes after the event of a random process (post-selection). In these cases, the probability of detecting the desired correlation drops exponentially with the number of entangled particles.

In an earlier experiment, the NIST group used a different technique to achieve 'surefire', or deterministic, entanglement of two particles by using a predetermined sequence of laser pulses[8]. In the new experiment the Mølmer–Sørensen procedure was followed, allowing them to entangle four particles with an appropriate single laser pulse. For quantum information processing, experiments with trapped and laser-cooled atoms are ultimately preferable to previous experiments with atoms and photons, in which entanglement is concluded from post-selection of randomly occurring coincidences rather than quantum state engineering.

Remember that these entangled atoms are a strangely correlated state of quantum matter: measurement of the state of a single atom (out of the four) is all that is needed to know the state of all the other atoms (Fig. 1). These would normally have to be found by other measurements if they were not entangled. Indeed, because the atoms 'know of each other', the outcome of the measurement contains the information of the entire system, not just of a subsystem. So entangled

states will have many applications. They can be used to improve the precision of a measurement beyond the standard quantum limit, for example for time and frequency standards. They will serve as a tool to study decoherence processes and as a further check on the predictions of quantum theory. Eventually they will be used for quantum information processing, in which an exponential growth in the performance of algorithms, without a similar increase in resources, will rely on the degree of entanglement. Last, but not least, many-particle entanglement will become an essential tool for realistic error correction in quantum computers. Now that many-particle push-button entanglement can be achieved with comparatively little effort, it will pave the

way for fundamental experiments and quantum state engineering. ∎

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Plant pathology

Pathogen-driven forest diversity

Wim H. van der Putten

Why are some forests more heterogeneous than others in terms of the tree species they contain? This is the problem addressed on page 278 of this issue by Packer and Clay[1]. Unusually, they look into the diversity of a temperate (black cherry) forest (Fig. 1), but they find that a hypothesis about tropical-rainforest diversity proposed in the 1970s by Janzen[2] and Connell[3] is of relevance here, too.

Janzen[2] and Connell[3] proposed that the diversity of trees in tropical rainforests results from the presence of organisms — specifically, herbivores — that thrive on only one species of tree. The occurrence and density of such specialized herbivores, especially insects, correlates strongly with the presence of their host trees. These tree-specific herbivores eat both mature trees and saplings, and the saplings are more vulnerable to defoliation. So, the establishment of young trees is constrained in the vicinity of their parents, and only those seedlings that are dispersed to some distance from mature trees of the same species may survive[2,3]. However, as the herbivores are loyal to just one type of tree, other tree species may become established in the vicinity of the herbivore's target, generating tree species diversity.

This hypothesis has been widely tested, but few studies have looked at the part played by soil pathogens in controlling species richness[4], and most have dealt with tropical rainforests rather than temperate forests. Packer and Clay[1] address both of these issues. They show that, because a particular soil pathogen (a fungus of the genus *Pythium*) lives on the roots of mature black cherry (*Prunus serotina*) trees, the dispersal of black cherry seeds away from their

Figure 1 **A black cherry (*Prunus serotina*) forest. Packer and Clay[1] propose that such forests owe their diversity in part to a cherry-tree-specific soil pathogen.**

parents is crucial for the establishment of saplings.

Packer and Clay's test site was a forest near Bloomington, Indiana. They observed that black cherry seedlings underneath mature black cherry trees died soon after germination. Seeds that were dispersed some distance from the parents, however, survived and produced new trees. In theory, the death of the former seedlings could have been the result of overcrowding, a phenomenon known as density-dependent mortality. However, Packer and Clay found that distance from mature trees was a better predictor of mortality than tree seedling density.

The authors then carried out a study in the greenhouse, using soil taken from underneath black cherry trees or from some distance away. They sterilized half of each soil sample, transferred the different samples to pots, and planted each pot with one or three seedlings. Mortality was high in unsterilized soil from underneath the black cherry trees,

but only when there were three seedlings together in one pot. In all other treatments, survival was close to 100%. The results hint at the existence of parent-associated soil pathogens, and indicate that the seedlings may have been culturing their own cause of death.

This cause of death was probably the soil pathogenic fungus *Pythium* spp., which Packer and Clay isolated from the roots of dying seedlings. Addition of cultured *Pythium* fungi to healthy seedlings produced an 80% death rate (compared with 30% in control samples). Packer and Clay succeeded in re-isolating the added fungus from these dying seedlings, confirming that a pathogen was indeed leading to seedling mortality. Other tree species did become established underneath black cherry trees in the forest, indicating that the pathogens were probably specific to black cherry trees. In this context, horticulturists are well aware that the replanting of fruit trees, including cherries, in orchards may fail because of soil pathogens. The simplest remedy is to plant another fruit species at the same time — a horticultural version of the naturally occurring situation in the black cherry forest.

Dispersal of black cherry seeds apparently affords them an opportunity to 'escape' from soil pathogens. But why hasn't this species developed resistance to its pathogens, as seen in the case of, for example, wild flax (*Linum marginale*) and the above-ground rust fungus *Melampsora lini*[5]? It is likely that the aggressiveness of soil pathogens, which can feed on both living and dead organic matter[6], allows little (if any) opportunity for the selection of pathogen-resistant host plant genotypes. Escape by dispersal may be the best option for plants in their arms race with soil pathogens, which are less easily dispersed than above-ground pathogens.

Might the existence of soil pathogens have led to selection for a dispersal trait in their plant hosts? In a comparison of six vegetative-propagating (clonal) plant species, the degree of vegetative outgrowth correlated positively with sensitivity to pathogens[7]. Sensitive plant species expanded so fast that the fungi could not keep up, leaving some plant parts uninfected. Another vegetative-propagating plant species, sand sedge (*Carex arenaria*), showed reduced branching of below-ground stems (rhizomes) and changed to unidirectional rhizome growth when exposed to patches of soil pathogens[8]. There might be a functional analogy between the escape strategies of these clonal plants and seed dispersal in the black cherry. The role of pathogens in the evolution of plant dispersal and other life-history traits (such as defence systems) certainly needs further study.

Where else is further investigation needed? Clearly, the particular species of *Pythium* that drives the mortality of black cherry seedlings needs to be identified, as does its specificity. It will also be important to find out how these (and other) soil pathogens contribute to ecological processes in the black cherry forest. Information about the persistence of the soil pathogens, the threshold levels of pathogen that cause seedling mortality, and the level of seed dispersal will build up our picture of how pathogens contribute to plant–soil feedback[9]. A similar picture is being worked out for long-term cycles of species composition in Douglas fir forests[10]. It would also be interesting to find out why *Pythium* is not suppressed by microbial antagonists underneath black cherry trees. In addition, follow-up experiments are required to explain why, in the greenhouse, the pathogen-induced mortality appeared only at high densities of seedlings.

The black cherry occurs naturally throughout temperate forests of eastern North America, and has also invaded northwestern Europe. Plant invasiveness has been related to escape from all sorts of natural enemies, but not to escape from natural soil pathogens. The studies by Packer and Clay[1] open the way for all of these issues to be investigated. In the meantime, we can conclude that Janzen and Connell's hypothesis about the diversity of tropical rainforests[2,3] has relevance for temperate black cherry forests and their enemies in the soil. ∎

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Hydrocarbon fuels

Hopes for a flame-free future

Kevin Kendall

What fuel will drive the coming century? As we look back over the past millennium, the progression of fuel usage has been from wood to coal to oil. Now, at the turn of the millennium, methane gas appears to be the preferred clean fuel of the major electricity generators. But we are moving inexorably towards hydrogen as the ultimate clean power source of the future, with fuel cells as the electrochemical conversion devices, producing electricity and heat at the point of need from hydrogen delivered through pipes[1]. Unfortunately, most hydrogen is still derived from hydrocarbons, making it expensive, and it is difficult to store and prone to explosion. These drawbacks will undoubtedly slow the onset of the hydrogen economy. In the meantime, can we use the hydrogen stored naturally in hydrocarbons, such as propane/butane (C_3H_8/C_4H_{10} or camping gas), to produce clean power? Nature seems to achieve this with ease through biochemical routes. On page 265 of this issue, Park *et al.*[2] describe a fuel cell that mimics this trick of nature.

Our problem is a lack of understanding of the electrochemical processes involved in hydrocarbon oxidation reactions. Although we oxidize about eight gigatonnes of hydrocarbon fuels annually, most of this is burnt in crude, dirty and wasteful flame processes in engines and burners[3]. We use so much yet know so little. By the end of this century,
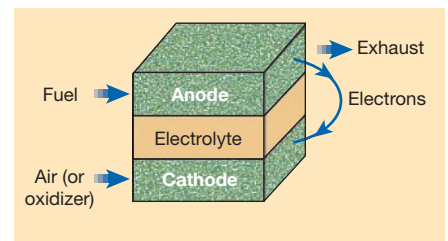

Figure 1 **A fuel cell works much like a battery. But unlike a battery it does not run down or need recharging, as long as it has a supply of fuel. Hydrogen is the ideal fuel because it reacts with oxygen from the air to produce an electric current and water, but pure hydrogen is expensive and prone to explosion. Park *et al.*[2] have developed a fuel cell that can directly oxidize the hydrogen stored in natural hydrocarbons found in regular fuels. They use a porous anode catalyst to encourage the chemical conversion of hydrocarbons without the undesirable carbon formation that usually fouls up the reaction. Such devices may become a viable alternative to the dirty and wasteful combustion processes by which most hydrocarbon fuels are oxidized today.**

these fiery combustion processes may be banned. Even now the trend is apparent: smoking is frowned upon; fires in forests are not permitted; dirty vehicles are penalized; and a new regulation has appeared in