predator numbers are high (P_2), prey numbers will crash. The full model for the system will have two equations, one for prey and one for predators, and we know that such two-dimensional models are perfectly capable of displaying cyclic behaviour.

We now see why the observation of the perfectly out-of-phase dynamics demonstrates that the rotifer–algal cycles could not be driven by the classical predator–prey mechanism. So what is the actual explanation? The path taken by the Cornell group to answer this question is an almost textbook example of how science is supposed to be done. First they advanced four competing hypotheses, suggested by various known features of algal and rotifer biology. Next they translated the hypotheses into mathematical models and contrasted model predictions with data. Only one model, based on the ability of algae to evolve rapidly in response to predation, successfully matched such features of data as period lengths and phase relationships[5]. This is a convincing result, and if we dealt with a natural system we would have to stop there because we cannot usually manipulate the genetic structure of field populations.

In the laboratory, however, such an experiment is possible, and the successful test reported by Yoshida *et al.*[1] provides the final and most decisive evidence of the rapid-evolution hypothesis. Thus, the out-of-phase cycles result from the following sequence of observed events: under intense predation, the prey population becomes dominated by clones that are resistant to predators; when most prey are resistant, the predators remain at low numbers even though prey abundance recovers; low predation pressure allows non-resistant clones to outcompete resistant ones; so predators can increase again, leading to another cycle.

The experimental demonstration that rapid evolution can drive population cycles means that ecologists will have to rethink several assumptions. To give just one example, there is a long-standing debate in population ecology on whether natural populations can exhibit chaotic dynamics. Chaos (in the mathematical sense) is irregular dynamical behaviour that looks as though it is driven by external random factors, but in fact is a result of internal workings of the system. Before the discovery of chaos, ecologists thought that all irregularities in the observed population dynamics were due to external factors such as fluctuations of climate. Now we realize that population interactions (including those between predators and prey) can also result in erratic-looking — chaotic — dynamics. Incidentally, the chaos controversy was the main reason why the Cornell group decided to study rotifer population cycles.

Some ecologists have argued that chaotic dynamics cause populations to crash to very low densities at which the probability of extinction is high, and that natural selection should therefore cause evolution away from chaos[6]. Since this argument was advanced, at least two examples of chaotic behaviour have been discovered: in the dynamics of the incidence of childhood diseases such as measles[7], and of population numbers of rodents such as voles and lemmings[8]. What is more important, however, is that the argument assumes that evolution occurs on much longer timescales than oscillations. But the results of Yoshida *et al.*[1] show that evolution can be an intrinsic part of oscillations, raising an exciting possibility that some populations might rapidly evolve both towards and away from chaos. Perhaps this is the explanation of the puzzling observation that some Finnish vole populations shift from a stable regime to oscillations, whereas others do precisely the reverse[9].

This is rank speculation, however, and will have to remain so because we cannot test it experimentally in natural systems. But in the laboratory much more is possible, as the study by Yoshida *et al.* shows. We can hope that in the near future we will see an experimental investigation of the possibility of rapid evolution to and away from chaos. ■

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Accelerator physics

In the wake of success

Robert Bingham

Particle accelerators tend to be large and expensive. But an alternative technology, which could result in more compact, cheaper machines, is proving its viability for the acceleration of subatomic particles.

Since the construction of the first particle accelerator in 1932, high-energy collisions of accelerated ions or subatomic particles (such as electrons and their antimatter counterpart, positrons) have proved a useful tool in physics research. But the escalating size and cost of future machines means that new, more compact acceleration techniques are being sought. In *Physical Review Letters*, Blue *et al.*[1] report results from a test facility at the Stanford Linear Accelerator Center (SLAC), California, that have great significance for the future of particle accelerators. Their success heralds an entirely new type of technology, the plasma wake-field accelerator.

When charged particles such as electrons or positrons pass across a gradient of electric field, they are accelerated — how much depends on the steepness of the gradient. In conventional accelerators, a radiofrequency electric field is generated inside metal (often superconductor) accelerator cavities. But the gradient can be turned up only so far before

ALAN SCHEIN/CORBIS

Figure 1 **The wake created by a boat is a familiar image, but it is also the inspiration for a new type of particle accelerator. Blue *et al.*[1] have demonstrated that waves in a hot, ionized plasma of gas can create a rippling electric field in their wake, and that this 'wake field' can accelerate subatomic particles.**

the field breaks down. A more attractive medium for the next generation of particle accelerators is a plasma — a gas of atoms that has been ionized into a soup of electrons and nuclei. Plasmas can support electric fields with strengths of around a hundred gigavolts per metre, which is orders of magnitude higher than conventional accelerators.

At the centre of Blue and colleagues' apparatus[1] is a chamber 1.4 metres long containing a hot plasma created from lithium atoms. The electron density in the plasma is about 1.8×10^{14} per cubic centimetre. When a tightly packed bunch, or pulse, of positrons is fired into the plasma, it creates a rippling electric field behind it, rather like the wake of a boat (Fig. 1), and hence the name 'wake field'. Inside the chamber, the positively charged particles in the pulse 'suck in' negatively charged electrons from the plasma. To restore charge neutrality, the displaced electrons then snap back, away from the pulse, but tend to overshoot their original positions. This oscillation in plasma electron density creates an oscillating electric wake field, moving behind the pulse (Fig. 2).

Roughly the first two-thirds of the positron pulse (which overall comprises about 10^{10} particles) lose energy in setting up the intense plasma wake field. From their initial energy of 28.5 gigaelectronvolts (GeV), these positrons decelerate at a rate of 49 megaelectronvolts (MeV) per metre. But the wake field they create accelerates the trailing third of the beam, increasing these particles' energies by almost 80 MeV over the length of the chamber, which corresponds to an accelerating gradient of 56 MeV per metre. The results are in excellent agreement with a three-dimensional simulation of the process, which predicted a peak energy gain of 78 MeV.

This is the first experiment to demonstrate energy gain by positrons in a plasma, and to use and accelerate particles that are at energies of interest for high-energy physics. (An existing electron–positron collider at SLAC used beams of particles with energies up to 50 GeV; the 'next linear collider', still at the planning stage, will have beam energies ultimately of 500 GeV.) To achieve this, Blue *et al.*[1] have had to overcome some tough practical problems. For example, the transportation and focusing of the positron pulse in the long plasma chamber is a remarkable achievement. The pulse shows no evidence of instabilities, particularly of the type known as 'hosing' instabilities[2], which induce transverse oscillations in the tail of the pulse that eventually destroy it. It is also significant that the positrons can propagate in the plasma without being annihilated by their electron antiparticles.

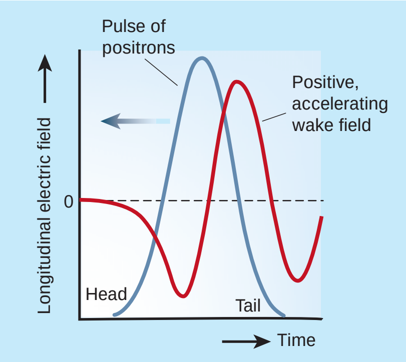

Figure 2 **Beam-driven plasma acceleration. A pulse of positrons (blue line) is fired into a plasma of lithium gas. The positively charged particle pulse attracts the negatively charged electrons in the plasma, drawing them in and creating an electric field in the wake of the pulse (red curve). Initially the longitudinal field dips negative, but then the displaced electrons snap back, overshooting their original positions and driving the longitudinal field to positive values. This strong, oscillating field is termed a 'wake field'. Although particles at the head of the pulse lose energy in setting up the wake field, particles in the tail are accelerated by it.**

High-gradient acceleration of electrons as well as positrons is necessary for the development of a compact electron–positron plasma collider. In fact, the positron pulse used by Blue *et al.*[1] could simply be replaced by an electron pulse. The wake field would then arise through a slightly different mechanism: the electron bunch expels all the plasma electrons within its radius (known as 'blow-out'), leaving a channel of positively charged ions or nuclei behind it; again, the oscillating charge density generates a wake field that will accelerate the tail-end of the bunch. Calculations show that the wake fields generated by positrons are weaker than for electrons, but the two would be comparable if, rather than being uniform, the plasma were shaped to form a hollow cylinder[3].

Instead of particles, a laser pulse can be used to set up an accelerating wake field in a plasma. In this case, the radiation pressure of the laser pushes the plasma electrons out of its path, creating oscillations in its wake. Previous experiments[4] on plasma wake fields driven by terawatt lasers have shown that particles injected into the wake field gain about 200 MeV of energy, but the acceleration has only been sustained over millimetre distances; Blue and colleagues' beam-driven acceleration is sustained over more than a metre.

Perhaps the first incarnation of the plasma wake-field accelerator will be within a conventional accelerator as a 'plasma afterburner'[5]. By introducing 10-m plasma sections into a linear collider that is many kilometres long, wake-field acceleration could be used to double the energy of conventionally accelerated particles. But wake-field acceleration comes at the price of decelerating the head of the particle bunch. To counteract this, plasma lenses are included in the design, between the afterburner and the collision point. Such lenses focus the particles into a tighter bunch, far more strongly than do the conventional magnetic variety[6]. The tighter the bunches are focused, the more likely are particles in opposing bunches to collide when they meet, so the rate of collisions is not degraded by inclusion of the afterburner.

The work presented by Blue *et al.*[1] marks the most significant progress so far in the field of advanced accelerator research. It is likely to have an impact on many fields, as compact accelerators are developed for wider applications, such as in medicine. And the impact on the way particle physics is done in this century will no doubt be profound. ■

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Ageing

Microarraying mortality

David Gems and Joshua J. McElwee

Understanding how we grow old is a long-sought goal. A new large-scale study of gene expression in worms allows us to glimpse the complex biochemistry of lifespan.

The past decade has seen dramatic developments in studies of the genetics of ageing and longevity, mostly involving model organisms such as the nematode worm *Caenorhabditis elegans*, baker's yeast, fruitflies and mice[1]. This has created considerable optimism that an understanding of the biology of ageing is within reach. So far, scores of ageing-related genes have been identified, in which altered activity increases longevity or accelerates ageing. But simply identifying these 'gerontogenes' often sheds no light on the real question at stake — what are the actual