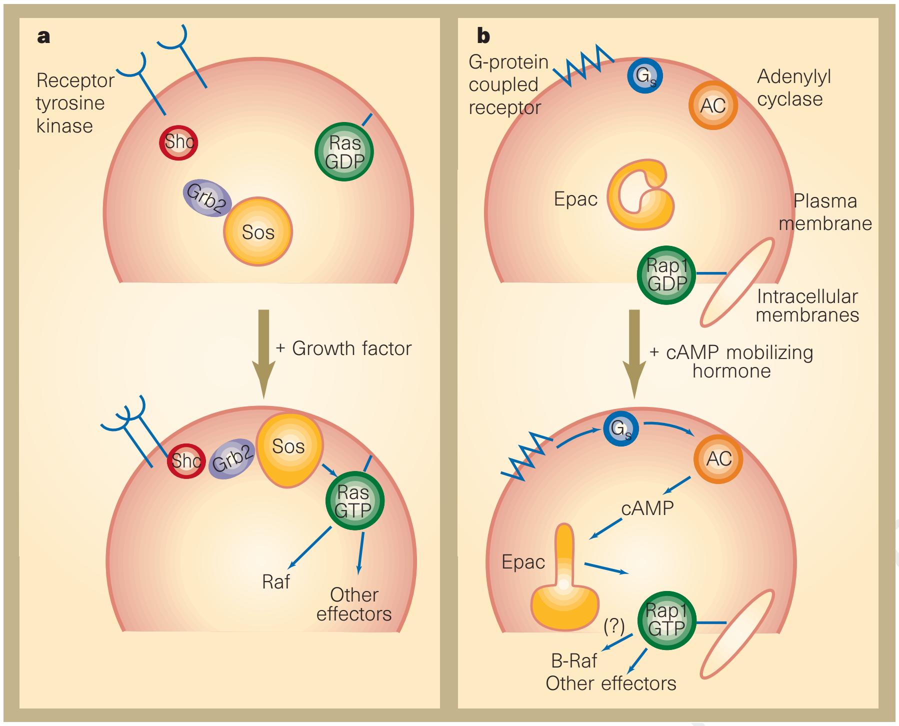

Figure 1 **Two types of regulatory system for Ras proteins.** a, **The classic Sos pathway. Activation of a growth-factor receptor tyrosine kinase leads to formation of complexes containing adaptor proteins (Shc and Grb2) and Sos (a guanine-nucleotide-exchange factor; GEF), at the plasma membrane where Ras is also located. Increased local concentration of Sos results in nucleotide exchange on Ras to form the active GTP-bound conformation, which stimulates several effector enzymes including Raf.** b, **Increases in the concentration of cyclic AMP, caused *in vivo* by hormone activation of G_s-coupled receptors, results in the binding of cAMP to Epac, a Rap1-specific GEF identified by de Rooij *et al.*[1]. This causes a conformational change leading to increased exchange activity towards Rap1, which is localized on intracellular membranes. GTP-bound Rap1 then activates effectors that may include B-Raf.**

after cAMP-dependent protein kinases and cyclic-nucleotide-gated ion channels.

Epac seems to fit into the category of second-messenger-stimulated GEFs (such as Ras-GRF and RasGRP), rather than the adaptor-regulated GEFs like Sos and C3G. However, this new work goes well beyond any previously done on Ras-family GEFs because de Rooij *et al.* used purified components to show, *in vitro*, that the activity of Epac towards Rap1 is allosterically stimulated on binding cAMP. They also deleted the cAMP-binding domain of Epac and found that this led to activation of Epac *in vitro*. This indicates that the cAMP-binding domain normally inhibits the exchange activity of Epac until cAMP binds, most likely causing a conformational change that relieves the inhibition.

This is the first time that the regulation of a Ras-family GEF has been reconstituted with defined components, and de Rooij *et al.* provide mechanistic detail at the molecular level that is still lacking for much more intensively studied GEFs such as Sos. After years spent languishing in the shadow of its flamboyant cousin, Rap1 has finally stepped into the limelight itself. Although there may still be disagreement as to the downstream effects of Rap1 on cell function, it is clearly a broadly used sensor for second messengers such as cAMP, Ca^{2+} and diacylglycerol. Moreover, the localization of Rap1 on intracellular membranes, which are readily accessible to soluble second messengers, may provide further clues to its function. □

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erratum

In the caption to Figure 1 of "Strategies for cutting carbon" (D. G. Victor, *Nature* 395, 837–838; 1998) the energy unit should be terawatt years, not terawatt hours. □

Daedalus

Watch this space

Empty space is a hive of activity. Particle–antiparticle pairs are being created out of nothing, all the time and everywhere, and vanishing again before their energy can violate the uncertainty principle. A high-energy particle collision nearby may provide the energy to stabilize such a virtual pair, making it real.

What velocity, asks Daedalus, is a virtual pair born with? The obvious answer is that it is created stationary; but relativity makes this impossible. Empty space has no reference frame to be stationary relative to. The best it can do, says Daedalus, is to arrive with some random velocity relative to local matter. And a truly random velocity, somewhere between plus infinity and minus infinity, is almost certain to be very large indeed.

Indeed, such pairs might constitute the long-sought tachyons, which travel faster than light and backwards in time. But Daedalus reckons that to external observers, new pairs will merely seem to be moving extremely close to the speed of light. Relativistic time-dilation will therefore stretch their internal timescale enormously. Even if a pair cannot last more than 10^{-20} or 10^{-30} seconds before vanishing again, to external observers the time will seem much longer. At almost the speed of light, the pair could travel some distance before disappearing. It could even collide with something, and (just as in a violent particle collision) be transformed into something detectable.

Daedalus would like to test this bold theory. Several large-scale experiments, such as neutrino telescopes and proton-decay detectors, consist of a large volume full of something, surrounded by a dense array of detectors all looking in. Daedalus proposes to pump out such an experiment, leaving the detectors watching a vacuum. Any ray, particle or pair that enters from outside will collide with and trigger two detectors, at its entry and exit points. But one created within the vacuum will trigger only one.

A successful outcome would provide all sorts of new high-energy events. If it detects newly created hydrogen atoms, it would support the 'continuous creation' theory, in which a steady-state Universe is maintained by the continuous appearance of new hydrogen throughout space. And if it sees only pairs with a well-defined velocity with respect to local matter, it will disprove relativity and resurrect that universal inertial reference frame, the ether.

David Jones

Strategies for cutting carbon

David G. Victor

What can be done to slow global warming? Huge new sources of carbon-free power may be needed. But other options also exist, and with so many uncertainties dogging predictions of technology and climate, choosing the best portfolio is hard.

The Earth is getting warmer, probably as a side-effect of human industry. The main culprit is carbon dioxide (CO_2), a by-product of burning fossil fuels for energy. On page 881 of this issue[1], Hoffert *et al.* examine one plausible scenario for future energy demand. They conclude that to stabilize the concentration of CO_2 in the atmosphere at twice pre-industrial levels will require a vast increase in the supply of carbon-free energy sources such as solar, wind and nuclear power.

In order to explore where policy-makers have leverage, Hoffert *et al.* express CO_2 emissions as the product of four variables: CO_2 released per unit of energy; energy consumed per unit of economic output; economic output per person; and the number of people.

There are good reasons not to meddle with the last two variables. Ideally, policy should limit CO_2 concentrations while doing minimum harm to the economy. Nor can politicians do much more to curb world population, which will probably stabilize at about 11 billion people[2]. Many countries may even attempt to increase their numbers in order to reverse the strains on productivity and social security that result when populations shrink and grey.

That leaves policy-makers two options: 'decarbonize' the energy system by lowering the quantity of carbon emitted per unit of energy[3], or improve energy efficiency (cutting the primary energy needed per unit of economic output).

Both of these numbers have improved over the past 150 years. On average, worldwide, the energy consumed per unit of economic output has declined at about 1% per year[4]. Hoffert *et al.* show that, if that rate remains constant, then stabilizing atmospheric CO_2 at 550 parts per million will require about 15 terawatts (TW) of carbon-free power by 2050, and even more thereafter. For comparison, today the world consumes about 13.5 TW of power altogether, of which no more than 3.4 TW are carbon free (Fig. 1). Creating so much carbon-free power would require a decrease in the carbon emission per energy unit of about 1% per year. The historical rate has been a more leisurely 0.3% per year[3]. The gap, conclude the authors, is huge.

This arithmetic is hardly controversial, but it leaves boulders unturned. Most importantly, Hoffert *et al.* omit economics from the analysis and so cannot explore the trade-offs that real policy must confront — such as the balance between carbon-free power and improved energy efficiency. For example, if policies to improve energy efficiency could accelerate the 1% annual decline in energy use per unit of economic output to 1.5%, then the carbon-free energy required would be cut in half (see Fig. 3 on page 883), and the urgency of investing in new power sources would wane. The energy system is full of fat: the useful energy output of many devices, such as illumination or locomotion, is only a few per cent of total energy input[5]. So large savings are quite possible.

Hoffert *et al.* may overstate the need for carbon-free power for another reason. Their baseline is the 1992 "a" scenario published by the Intergovernmental Panel on Climate Change, which assumes that coal, the most carbon-intensive fossil fuel, remains one of the main energy sources. So carbon emissions would be high, and stabilizing atmospheric CO_2 requires a lot of carbon-free power. But it may well be that even without a deliberate policy to slow global warming, energy production comes to be dominated by less carbonaceous natural gas, or by

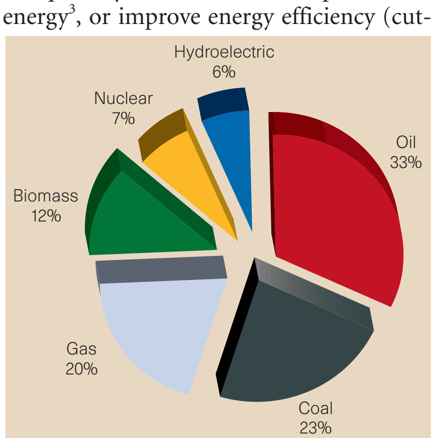

Figure 1 **Global energy consumption in 1996, totalling 13.5 terawatt hours. About 25% is carbon free. Of the rest, coal releases 790 million tonnes of carbon per terawatt hour; oil 610; gas 470.**

JOINT EUROPEAN TORUS

KLEIN/HUBERT/STILL PICTURES

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Figure 2 **Three ways to curb carbon: nuclear fusion (top left), a carbon-free technology that is still not commercially viable; tree plantations (top right), which can remove carbon from the atmosphere or provide fuel wood with practically no net carbon emission; and energy-efficient light bulbs. Deciding on which are best depends on many factors, including expected future costs.**

carbon-free nuclear and biomass fuels[6], yielding much lower carbon emissions and less need to supply still more carbon-free power.

Politicians should also consider options for withdrawing carbon from the atmosphere by planting trees, improving soil management and disposing of CO_2 captured from the smokestacks of power plants before it is released to the atmosphere. That would lower the need for carbon-free power and is also likely to be a cost-effective option, especially during the next few decades, before radically new energy systems are available (Fig. 2).

Hoffert *et al.* are right to emphasize that to curb global warming will entail massive technological change. Research and development is needed to make new technologies viable, so it is worrisome that public energy-related R&D is declining in nearly every industrialized country[7,8]. In the United States — the biggest spender on energy R&D — the total funding fell by 40% from 1985 to 1994, and worse was to come: gas and electricity companies cut basic research by two-thirds[9] from 1995 to 1996, as restructuring and deregulation of energy markets led them to concentrate on short-term returns. Society as a whole prospers by the new concepts that emerge from basic research, but competitive companies have little incentive to make the necessary long-term investments. Nevertheless, efforts in some countries to reverse the trend are bearing fruit.

To slow global warming will require policies that penalize carbon emission and encourage higher investment in energy R&D. Those policies can be more effective if guided by economic and engineering analysis, but only if the models used to assess long-term global-warming costs and benefits include an improved representation of technological change[10]. Research is also needed to identify the best policies for directing R&D. Hoffert *et al.* suggest something on the scale of the Manhattan Project or Apollo Program as models. But unlike those publicly funded crash programmes, an effective energy R&D programme must heed market conditions — after all, the market will dictate which technologies are eventually adopted.

And there is an even more fundamental question to be answered: what should be the objective of global-warming policy? Many studies assume that we should aim to stabilize atmospheric CO_2 at 550 parts per million, a convenient number that is about twice the concentration before the industrial revolution, and about 50% more than today's. But there is little solid evidence to justify that choice of number; nor is it clear whether any single number can express the damage that could result from global warming. For now, taking action on global warming is akin to buying insurance with an unknown premium against unknown hazards. Investing in new technology may be a good hedge against that uncertain future, but exactly what to do is still unclear. □

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Perception

Measuring distance in two dimensions

Walter Metzner

Depth perception is a tricky task. A three-dimensional environment is first mapped onto a two-dimensional array of receptor cells (such as the photoreceptors in eyes; auditory receptors in the inner ear; mechanoreceptors in the lateral-line system of fish and aquatic amphibians; or, in some fish, also electroreceptors). Animals then have to reconstruct a three-dimensional image of their world in the brain, and they have come up with many ways to do so.

The work by von der Emde *et al.* (page 890 of this issue[1]) shows us yet another way that nature has found to achieve this end. The authors show that weakly electric fish (*Gnathonemus petersii*; Fig. 1) can measure the distance of stationary objects unambiguously by instantaneously analysing the electric image of objects with a single array of electroreceptors embedded in their skin. Other animals manage the same job equally well only by using at least a pair of sense organs, such as the two eyes; or, if they use only a single sense organ, they take two or more snapshots of the same object, mostly from different angles[2–5].

Such is not the case with weakly electric fish. These nocturnal animals inhabit freshwater ponds and streams in South America and Africa. They produce weakly electric fields with an electric organ situated in the tail region and sense the distortions caused by the surrounding objects with their electroreceptors. Depending on its shape, location, electrical properties and distance, an object will alter the sensory feedback of a fish's electric organ discharges in a characteristic fashion, resulting in a specific 'electrical image' of the object on the fish's body surface. This image is then scanned by the array of electroreceptors in the fish's skin that transfer the information to the brain. The brain deciphers this code and determines the type and location of the object.

A problem in this context, however, is the ambiguity between object size and distance: a particular object might appear to be small because it is far away or simply because it *is* small. Are electric fish able to resolve this dilemma? And if so, how? In a series of behavioural discrimination experiments, von der Emde *et al.*[1] show that their fish can indeed determine the distance of objects independently of the objects' size, shape or constituent material. Surprisingly, however, when the authors measured the electrical images produced by various cubes, pyramids and spheres placed in an animal's electric field, they found no single physical parameter that could have provided the fish with an unambiguous cue. But after further data analysis, they identified one particular combination of parameters that was unequivocally correlated with object distance: the ratio of the 'slope' of the electrical image (that is, how 'fuzzy' it is at the edges) over its maximum amplitude.

To make this intuitively a bit more comprehensible, compare this combination of electrosensory parameters with visual cues. Unlike visual objects, electrical objects create larger images the further away they are. So, as shown in Fig. 2, an electrical image is in this regard better compared to the shadow an object casts on a screen: the size of the shadow increases with distance and the edges of the shadow become fuzzier. This results in a lower ratio of maximum darkness of the image over maximum slope of intensity change at the image's edge; it could, thought von der Emde *et al.*, be the way in which weakly electrical fish sense distance.

To test their hypothesis, the authors applied behavioural experimentalism at its best — they cheated the experimental animal. This is the highlight of the paper. The authors took advantage of an 'electrical illusion': their slope/amplitude measurements revealed that spheres always yielded slightly lower ratios than any other object shape, because the round contour of a sphere creates a less intense and more