Rethinking Hydrogen Cars

David W. Keith and Alexander E. Farrell

Support for hydrogen cars has reached new heights, especially for fuel-cell vehicles that use hydrogen directly. The largest effort is President Bush's FreedomCAR and Fuel Initiative, which amounts to \$1.7 billion over 5 years (*1*). Critics suggest the plan is a tactical move to avoid policies such as strict fuel efficiency standards that could be readily implemented today (*2*). Here, we take a longer-term strategic view of energy policy and argue against early adoption of hydrogen cars.

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The introduction of any new transportation fuel is a rare, difficult, and uncertain venture—it demands a linked introduction of a new fuel distribution system and new vehicles, because neither is useful without the other (*3*). Although technically feasible, a hydrogen refueling infrastructure would be expensive: initial cost would likely exceed \$5000 per vehicle even if one assumes large economies of scale (*4*). The cars themselves will also likely be expensive. If hydrogen cars are ever to match the performance of current vehicles at a reasonable cost—particularly fueling convenience, range, and size—technological breakthroughs in hydrogen storage and energy conversion will be required.

Like electricity, hydrogen is an energy carrier that must be produced from a primary energy source. Today, hydrogen is produced from natural gas on a large scale and at low cost: hydrogen production consumes ~2% of U.S. primary energy, and at the point of production, it costs less than gasoline per-unit of energy. Although hydrogen production is simple, as a low-heating-value, low-boiling-point gas, it is inherently expensive to transport, store, and distribute—all strong disadvantages for a transportation fuel.

Hydrogen offers three principal advantages that may offset its disadvantages and may address important policy goals: (i) it can be burned cleanly or used in fuel cells and so can reduce air pollution; (ii) it emits no CO_2 at point of use; and (iii) it can be produced from diverse energy sources and so can reduce oil dependence.

Air Quality

Hydrogen could essentially eliminate vehicular emissions, but the cost of reducing NO_x emissions (for example) with hydrogen will be on the order of \$1 million per tonne NO_2 (*5*). In contrast, meeting the EPA's new Tier 2 standards will reduce emissions for about \$2000 per tonne, and inspection and maintenance programs will cost about \$4000 per tonne and scrappage programs (voluntary programs offering bounties for old vehicles), less than \$10,000 per tonne (*6*–*8*). The cost of reducing NO_x emissions from electricity production is in the same range. Similar comparisons can be made for other important air pollutants.

It is comparatively expensive to reduce pollutant emissions by using hydrogen because regulation-driven technological innovation has reduced emissions from gasoline-powered cars to the point where they have very low emissions per-unit-energy compared with other sectors and other transportation modes (see table, page 316). This trend will continue, reducing the benefit of zero-emission hydrogen vehicles, particularly because many technologies (e.g., electric drive) can be used on both platforms.

Hydrogen could largely eliminate the problem of "high emitters"—the few poorly designed or maintained cars that account for most automobile emission—because hydrogen cars do not have high-emission failure modes. Nevertheless, the approaches listed above, possibly in conjunction with roadside emission monitoring and other advanced techniques, provide far more cost-effective solutions (*9*).

Climate Change

A near-zero-emission source of hydrogen is required if hydrogen cars are to reduce CO_2 emissions substantially. The cost of CO_2-neutral hydrogen turns on the viability of CO_2 capture and storage (CCS) because it is currently much cheaper to make hydrogen from fossil feedstocks such as coal or gas than from other sources (*10*, *11*). It is substantially easier to capture CO_2 from hydrogen production than from electric power plants because the CO_2 is at high partial pressure—indeed many existing facilities already vent nearly pure CO_2. If CO_2 storage in geological reservoirs (or perhaps elsewhere) is socially acceptable and can be widely implemented, then the cost premium for CO_2-neutral hydrogen will likely be less than 30%. Even with these assumptions, hydrogen cars will be an expensive CO_2 mitigation option because of the high cost of vehicles and refueling infrastructure. Costs may exceed \$1000 per tonne of carbon if hydrogen cars are to match the performance of evolved conventional vehicles (*12*). With consistent assumptions about CCS, reducing electric sector emissions by 50%—equivalent to eliminating CO_2 emissions from all cars—is likely to cost between \$75 and \$150/tC (*13*, *14*).

If CCS proves unacceptable, the cost of reducing CO_2 emissions with hydrogen cars will be much higher. Electrolysis using non-fossil electricity is a leading option, but it places substantial extra costs and inefficiencies between energy source and end use. Until CO_2 emissions from electricity generation are virtually eliminated, it will be far more cost-effective to use new CO_2-neutral electricity (e.g., wind or nuclear) to reduce emissions by substituting for fossil-generated electricity.

Therefore, whether CCS is viable or not, it will be more cost-effective to reduce CO_2 emissions in the electric sector than to do so using hydrogen cars. For several decades, the most cost-effective method to reduce CO_2 emissions from cars will be to increase fuel efficiency. A recent National Academy of Sciences study concluded, for example, that 12 to 42% improvements in the fuel economy of light-duty vehicles would pay for themselves in lifetime fuel savings (*15*), and these estimates probably understate the potential because they exclude diesels and hybrids.

Energy Security

Improving fuel efficiency would help moderate oil consumption along with CO_2 emissions. In addition, there are two other options to increase energy security: strategic petroleum reserves (SPRs) and petroleum substitutes. Several industrial countries have SPRs to manage supply interruptions; the U.S. alone stores about 50 days worth of imports. However, management of SPR assets has been relatively ineffective. Proposals to use the SPR to limit price spikes, rather than ill-defined "emergencies," to allow market participants to bid on new SPR options contracts, or to turn SPR management over to an independent agency all deserve serious consideration.

Petroleum substitutes include synthetic hydrocarbon fuels derived from fossil feedstocks (coal) or from biomass including cellulosic bio-ethanol and bio-diesel. It has long been assumed that manufacture of synfuels from coal would produce unacceptably large CO_2 emissions, but as with hydrogen

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EMISSIONS FROM U.S. ELECTRICITY AND TRANSPORTATION

		SO_x emissions			NO_x emissions		
	CO_2	Percentage	SO_2 per GJ of fuel (kg SO_2/GJ)		Percentage	NO_2 per GJ of fuel (kg NO_2/GJ)	
Sector	(% total)	(% total)	Current	Est. in 2010	(% total)	Current	Est. in 2010
Cars and light trucks	19	1	0.02	<0.005	18	0.25	0.01
Other transportation	14	5	0.08		39	0.70	
Fossil fuel electricity	41	70	0.40	0.28	32	0.24	0.12

Emissions from electricity and transportation in the United States. These pollutants include the most important contributors to fine-particle formation, the air pollutant with the greatest health impacts. Emission rates in 2010 are based on pending emission control regulations (*21*); all other values are current sectoral emissions (*22*). Regulatory standards for the rest of the transportation sector are generally weaker than they are for cars.

production, CCS could change the game because it is comparatively easy to capture CO_2 from synfuel production. Indeed, CO_2 from the major U.S. coal-to-gas facility is currently being captured and stored. Bio-fuel production with CCS would have net negative CO_2 emissions, which could lower the cost of mitigation (*16*).

Such petroleum substitutes are cost-competitive with hydrogen, and because they can be stored, transported, and distributed through the existing infrastructure and used in existing vehicles, they can be introduced more quickly with much less technological risk than could hydrogen.

Hydrogen's Role as a Transportation Fuel

Global CO_2 emissions must decline by about an order of magnitude in order to stabilize atmospheric concentrations, so major emission reductions will eventually be required from cars. Cost-effective climate policy, however, starts with low-cost emissions reductions and proceeds at a measured pace. Analysis of optimal climate policy typically shows that to stabilize concentrations below a doubling of preindustrial levels, overall emissions do not need to be reduced by more than 30% below business-as-usual until after 2040 (*17*). When emission mitigation opportunities across the economy are ordered by their cost (to form a supply curve), deep reductions in automobile emissions are not in the cheapest 30%. All else equal, it is therefore wasteful to devote substantial resources to achieving deep reductions in auto emissions until after 2040 (*18*). Only then will radical new technologies likely be needed. Hydrogen cars should be seen as one of several long-run options, but they make no sense any time soon.

If we were certain that hydrogen fuel was the only long-run solution to eliminating CO_2 emissions from cars, then it might make sense to focus R&D now, even though widespread deployment is decades away. If, however, we accept that there is considerable uncertainty about the optimum long-run solution, then early commitment to hydrogen fuel is unwise because it risks technological lock-in.

If it were necessary to introduce hydrogen into the transportation sector, a wiser strategy would focus on transportation modes other than cars (*19*). Hydrogen-powered heavy freight vehicles, such as ships, trains, and large trucks, could provide greater air-quality benefits (they have much higher emission intensities, see table) and could be more easily implemented (they require a much smaller distribution infrastructure) and make less stringent demands on the performance of hydrogen storage systems (onboard space has a smaller premium).

Despite the arguments presented above and despite criticism of tactical aspects of the Administration's new programs, there is a deep and widespread interest in hydrogen cars. An unusual coalition—from environmentalists and futurists to auto executives, oil barons, and nuclear engineers—advocates the deployment of hydrogen cars as a long-run strategic goal for climate and energy policy, and many share a broader vision of a "hydrogen economy" (*20*). However, enthusiasm for hydrogen cars conceals widely divergent visions of the future aimed at incompatible goals. Some would like to manufacture hydrogen using nuclear power, others using solar energy. Some seek energy independence, others, to stop climate change.

The appeal of hydrogen arises, in part, because it is a pristine high-technology solution that promises to resolve multiple problems simultaneously by making a clean break from present technologies and avoiding long-standing controversies over issues like drilling in the Arctic National Wildlife Reserve and emissions from sport utility vehicles (SUVs). It is an attractive vision that demands serious investigation, but it's not a sure thing. Transportation R&D should be broadly based, and should focus on basic enabling technologies rather than on a rush to deploy hydrogen cars.

Finally, research must not stand in the way of action. Near-term strategies to address the serious challenges posed by air pollution, climate change, and petroleum dependence should focus on emissions from electricity generation and freight transport, on strategic petroleum reserves, on energy efficiency, and on petroleum substitutes.

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LETTERS

Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 6 months or issues of general interest. They can be submitted by e-mail (science_letters@aaas.org), the Web (www.letter2science.org), or regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.

Hydrogen Cars and Water Vapor

D. W. KEITH AND A. E. FARRELL'S POLICY FORUM "Rethinking hydrogen cars" (18 July, p. 315) draws attention to the need for broad technology assessment of a popular policy alternative. In the pursuit of this new technology, the focus on the problem to be solved can lead to insufficient attention being paid to new environmental problems that might follow from its adoption. These new problems become tomorrow's unanticipated consequences, and the cycle begins again. This cycle could be dampened, however, with a thorough assessment of the new technology before it has completed development.

This cycle is currently under way with hydrogen fuel cells. As fuel cell cars are suggested as a solution to global climate change caused by rising levels of greenhouse gas emissions, they are frequently misidentified as "zero-emissions vehicles." Fuel cell vehicles emit water vapor. A global fleet could have the potential to emit amounts large enough to affect local or regional distribution of water vapor.

Variation in water vapor affects local, regional, and global climates (*1*). Data on such effects are sparse because of complexities in the water vapor life cycle. However, our preliminary calculations indicate that a complete shift to fuel cell vehicles would do little to slow water vapor emissions, which presumably have increased perceptibly in some metropolitan locations through the growth in use of internal combustion engines. In some locations, changes in relative humidity related to human activity have arguably affected local and regional climate (*2*, *3*). Depending on the fuel cell technologies actually employed, relative humidity in some locales might conceivably increase by an amount greater than with internal combustion engines. This increase could lead to shifts in local or regional precipitation or temperature patterns, with discernible effects on people and ecosystems.

> **"In the case of hydrogen cars, the cure may indeed be better than the disease, but we should make sure before taking our medicine."**
>
> –*PIELKE* ET AL.

The broad environmental effects of fuel cell vehicles are an issue worth addressing via a technology assessment before implementing a solution (*4*). Not all problems can be anticipated in this manner, but if some can, then the effort will have been well spent (*5*). In the case of hydrogen cars, the cure may indeed be better than the disease, but we should make sure before taking our medicine.

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Response

WE AGREE WITH PIELKE *ET AL.* ON THE IMPORTANCE of examining the environmental and other implications of new technology early in its development cycle. We are skeptical, however, that water vapor produced by combustion can have any important effect except when it is emitted in the stratosphere. The global emission of water due to oxidation of fossil fuels is of order 10^5 times smaller than the natural hydrological cycle, and even in cities, the humidity perturbation due to oxidation of fuels is likely to be small compared with other human impacts on near-surface water vapor, such as the land use changes described in Pielke *et al.*'s reference (*2*).

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What About the Shortcuts?

IN THEIR POLICY FORUM "RETHINKING hydrogen cars" (18 July, p. 315), D. W. Keith and A. E. Farrell overlook many shortcuts to early deployment of attractive and profitable hydrogen cars. Their over-$5000-per-car cost estimate for hydrogen fueling infrastructure is an order of magnitude above authoritative engineering-economic calculations for filling-station–scale methane reformers (*1*) now being commercialized, using off-peak distribution capacity for natural gas and not materially increasing net natural-gas demand (*2*). Their claim of needed "breakthroughs in hydrogen storage" ignores a 2000 design for a manufacturable, production-costed, cost-competitive, uncompromised, quintupled-efficiency midsize SUV (*3*, *4*) using currently commercial compressed-hydrogen tanks. The marginal cost of reducing NO_x emissions with hydrogen is zero, not ~$1 million/ton, if reducing NO_x is a free byproduct of a hydrogen transition that is profitable for other reasons (*2*). And while ultimately eliminating automotive CO_2 will require either carbon sequestration or a climate-safe source of cheap electricity, carbon-releasing gas-reformation hydrogen in an efficient hydrogen-ready car (*3*, *4*), as part of an integrated vehicles-and-buildings hydrogen transition strategy (*5*), would reduce CO_2 emissions per kilometer by ~2 to 5 times at negative cost (*3*, *4*), or officially by 2.5 times (*6*)—surely an important interim step worth pursuing with due deliberate speed.

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Response

WE ARE DEEPLY SKEPTICAL OF TOTTEN'S suggestion that hydrogen fuel cell vehicles (H_2-FCVs) could cut CO_2 emissions by as much as a factor 2 to 5 at negative cost. In part, our differences arise from divergent judgments about how best to estimate near-term costs. For instance, in arguing that our estimate was an order of magnitude too high, Totten cites an "authoritative engineering-economic" estimate of infrastructure cost-per-car that in fact contains few technical details about the fueling system in question and is authored by the president of a company trying to bring such systems to market. A recent National Renewable Energy Laboratory–sponsored study (*1*) by a disinterested consultancy that is rich in technical and economic detail strongly supports our estimate, which was itself based on a study by Argonne National Laboratory (*2*). Our estimate may well have been a bit high, but is not likely wrong by an order of magnitude.

> **"Over the long term, alternatives to petroleum fuels are needed, and hydrogen is the only energy carrier that offers the prospect of a domestically based zero-emissions transportation fuel."**
>
> –GARMAN

More fundamental differences arise from choice of reference vehicle rather than from disagreement about the ultimate performance attainable from H_2-FCVs. Totten's factor of 5, for example, arises from comparison of an as-yet-unmanufactured concept car that embodies many advanced efficiency-enhancing technologies (such as ultralow mass composite body structure, a hybrid drive system, and advanced tires) to a reference vehicle with current technologies and unimpressive fuel efficiency. More realistic analyses (*3*, *4*) take pains to make apples-to-apples comparisons, ensuring that all simulated vehicles deliver the same performance (e.g., range, interior volume, and so forth) and take equivalent advantage of technical advances in vehicle mass, hybrid drive systems, and other technologies. The relevant questions are, how much better are H_2-FCVs than similarly advanced (e.g., hybrid-drive) conventionally fueled vehicles, and, at what cost is the emissions improvement, if any, purchased? By attributing all emission reductions to hydrogen, Totten grossly exaggerates the benefits of switching to hydrogen fuel.

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The Bush Administration and Hydrogen

TWO RECENT ARTICLES, "POTENTIAL environmental impact of a hydrogen economy on the stratosphere" (T. K. Tromp *et al.*, Reports, 13 June, p. 1740) and "Rethinking hydrogen cars" (D. W. Keith, A. E. Farrell, Policy Forum, 18 July, p. 315), may have caused some to question the goals and objectives of President Bush's FreedomCAR and Hydrogen Fuel Initiative. Although we welcome rigorous scrutiny and public discussion, we must, for the record, respond to several errors and mischaracterizations in the articles.

We believe that Tromp *et al.* grossly overstated the estimates of hydrogen (10 to 20%) that would escape from hydrogen production, distribution, and refueling systems. These losses were based on a paper on liquid hydrogen (*1*), which has inherently higher release rates because of the need to release "boil off" through pressure valves. Our work, on the other hand, is focused on gaseous hydrogen. Moreover, because of safety and other considerations, hydrogen refueling systems, unlike gasoline refueling, will be designed as "closed" systems with negligible losses to the environment. We have already demonstrated such systems at prototype refueling stations. Remarkably, the authors assumed an annual loss of 60 million metric tons, which ironically is roughly the amount of hydrogen we estimate would be needed to fuel an entire domestic fleet of 230 million light-duty hydrogen fuel cell vehicles. Obviously, if we only need about 60 million metric tons to fuel the entire domestic light-duty fleet, leakage rates would be far less.

Keith and Farrell state that they are taking "a longer-term strategic view of energy policy," yet they offer only short-term measures that ultimately will not solve the United States' dependence on foreign oil or address air pollution and greenhouse gas concerns. We agree that

> **"...policies to address current high emitters, to improve average vehicle efficiency, and to reduce emissions of CO_2 and pollutants in the electric power sector will be highly cost-effective and should be aggressively pursued in the near term, while long-term goals can be addressed by research on biofuels and synthetic petroleum, in addition to hydrogen."**
>
> –KEITH AND FARRELL

short-term measures are important, which is why the Bush Administration advocated hybrid vehicle tax credits, raised Corporate Average Fuel Economy (CAFE) standards for the first time since the 1996 model year (the greatest increase in fuel economy standards in the past 20 years), and supports a renewable fuels standard to increase ethanol production and use. But these are interim strategies that can only briefly moderate, and cannot completely eliminate, our increasing demand for foreign oil. Over the long term, alternatives to petroleum fuels are needed, and hydrogen is the only energy carrier that offers the prospect of a domestically based zero-emissions transportation fuel.

The Department of Energy is not rushing to deploy hydrogen cars, as Keith and Farrell seem to suggest and as some in Congress are urging us to do. Instead, we are engaged in a long-term research and development effort focused on key enabling technologies. Only after these technologies progress to the point where they can meet customer expectations, and only when industry can establish a business case for substantial investments in hydrogen infrastructure, will hydrogen fuel cell cars be successfully commercialized in large numbers. Although some fuel cell vehicles are on the road today, we believe it is unlikely that affordable fuel cell vehicles will be produced for mass consumer markets until sometime after 2015.

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Response

GARMAN ARGUES, CORRECTLY, THAT IF PEOPLE make very little molecular hydrogen, then very little can leak into the atmosphere. However, he considers only the 53 megatons of annual hydrogen production required for a single program in a single country—one or two orders of magnitude smaller than the scale a future hydrogen economy must take if it is to significantly impact global fossil fuel use.

The Department of Energy (DOE) has estimated that 265 megatons of hydrogen per year would be needed to meet the expected transportation energy needs, alone, of the United States in 2020 (*1*). More broadly, fossil fuel use in the United States in the year 2000 produced 3.3 TW of energy, and 3.5 gigatons of hydrogen would have been required to completely replace these fossil fuels with fuel cell technologies (*1*). Globally, fossil fuels produced about 10 TW of energy in 2000, and 10.6 gigatons of hydrogen would have been required to replace them. By the year 2020, these numbers are expected to increase by factors of about one-third. That is, the scale of H_2 production Garman suggests amounts to less than 1% of the global energy demand by the year 2020.

While few have suggested that molecular hydrogen will be the medium for most or all energy use within our lifetimes, much of the interest in a hydrogen economy comes from its potential to significantly reduce fossil fuel use. Although people are likely to disagree on what is significant, one definition comes from studies of greenhouse warming, which suggest that 30% reduction in CO_2 emissions by 2020 will be needed to stave off the worst consequences (*2*). If this 30% were achieved through use of hydrogen fuel cell technologies (in the case that H_2 comes from sources with low CO_2 emissions), global annual production of hydrogen must be about 4.7 gigatons per year. Note that this calculation, based on DOE estimates of the relationship between energy use and H_2 production, differs from the

Schultz *et al.* estimate of H_2 needed for 50% reduction in fossil fuel use (*3*, *4*); the source of this discrepancy is unclear to us.

Garman also takes exception with our suggestion that economy-wide leakage of up to 10 to 20% should be considered. However, more recent estimates, including one by a broad and highly qualified group, are consistent with our discussion. The recent DOE report cited above (*1*) states: "Leakage rates much greater than 1% are likely if no action is taken to engineer systems in advance to minimize hydrogen leakage."

This report does not discuss the possibility that economy-wide leakage rates could be less than 1%. Similarly, Schultz *et al.* (*3*) adopt loss rates of 3% (preferred) to 10% (extreme) for their recent model and describe the upper limit that we discussed as "possible but very unlikely [for] safety and economic reasons." Prather's recent calculations also make use of the 3 to 10% estimate (*4*). Combination of Schultz *et al.*'s preferred leakage rate (3%) with the H_2 production needed to replace one-third of projected global fossil fuel use in 2020 results in expected emissions of about 140 megatons per year—similar to the current amount in the entire atmosphere, or $1.8^{+1.5}_{-0.5}$ times current annual production from all sources (*5*). There are insufficient data to project how such a rise in hydrogen sources would translate into increased steady-state atmospheric concentrations, because the current rate of soil uptake and its dependence on atmospheric concentration are poorly known. Nevertheless, it seems reasonable to consider that factors of several increases in sources could lead to factors of several increases in concentration.

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Response

GARMAN'S CLAIM THAT WE OFFER NO measures to address air pollution or greenhouse gas emissions is simply not true. To restate, policies to address current high emitters, to improve average vehicle efficiency, and to reduce emissions of CO_2 and pollutants in the electric power sector will be highly cost-effective and should be aggressively pursued in the near term, while long-term goals can be addressed by research on biofuels and synthetic petroleum, in addition to hydrogen.

The Bush Administration's minor (7%) increases in fuel economy for the least efficient half of light-duty vehicles and small changes in tax credits are indeed short-term measures. The new light-truck fuel economy standard will only slow, not reverse, the steady decline in average light-duty fuel economy the United States has experienced since 1986. Moreover, the rhetoric of hydrogen cars silently assumes that technological advances will be deployed by industry to achieve public policy goals, despite the pervasive evidence that, absent regulation, firms (correctly) use new technologies to increase returns and market share.

We know of no conclusive evidence that hydrogen is a better long-term transportation fuel than synthetic hydrocarbons, electricity, biofuels, or some combination, let alone proof that it is the "only energy carrier that offers the prospect of a domestically based zero-emissions transportation fuel." We commend the Department of Energy's hydrogen research program for focusing on onboard storage—a key issue. However, given that the solutions we recommend—efficiency and petroleum substitutes—will be the cheapest ways to reduce petroleum use and CO_2 emissions for several decades, a target for the deployment of hydrogen cars in 2015 is an example of the government picking the technological winner and rushing to judgment.

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CORRECTIONS AND CLARIFICATIONS:

News Focus: "Physicists honored for their medical insights" by G. Vogel (17 Oct., p. 382). Paul Lauterbur, winner of the 2003 Nobel Prize in physiology or medicine, is a physical chemist, not a physicist.

Letters: "Response" by T. A. Gardner *et al.* (17 Oct., p. 393). In the response, the second author of the letter was incorrectly referred to as Wade. His name is John R. Ware.

News Focus: "A boost for tumor starvation" by J. Marx (25 July, p. 452). Two errors appeared on line 10 of the table of antiangiogenic drugs undergoing clinical trials. The correct full name of PTK787 is PTK787/ZK 222584. Also, the drug is being developed by both Schering AG and Novartis Pharmaceuticals Corporation, rather than Abbot Laboratories, as originally attributed.