Discovery and invention

Sir Martin Rees

In Victorian times, the national scientific enterprise was minuscule by today's standards. Yet the commitment to the public understanding of science was not. The marvellous national and civic museums – cathedrals of discovery and invention – consumed large resources by the standards of that time. Our forebears believed, as fervently as the British Association does now, that the UK's achievements in science, engineering, and technology deserve wider appreciation, that science is part of our culture, and that how it is applied should concern us all.

The 'public' for science

Science and engineering had a high profile. Most people have heard of the great nineteenth century engineers – Brunel, Telford, and so forth. It is actually harder to name living engineers even though their marvels surpass those of earlier centuries. And it was not just the practical men – the 'wealth creators' – who earned public acclaim. Think of Darwin: his insights had no practical payoff, but he was a revered figure because he changed the way humans see their place in nature.

So what about public attitudes today, as we approach the twenty-first century? We have all read the outcome of scientific quizzes, in newspapers and elsewhere, which reveal that many can hardly tell a proton from a protein. Such people can (partially) excuse themselves by claiming that the facts in themselves are not the essence. What matters is having a rough 'intellectual map': so that we can appreciate our natural environment; so that the artefacts that surround us do not seem mysterious; and so that we can all participate, critically, in shaping how technologies are developed and applied.

Everyone needs a basis for assessing when scientific claims are credible and when they are not. Noisy controversy does not always signify evenly balanced arguments; but most issues that rightly concern us involve genuine scientific uncertainties, and major trade offs. The ethical and social implications of (for instance) *in vitro* fertilisation from foetuses, genetic screening, or environmental degradation can and should be widely appreciated and discussed, even by people who do not understand (and may not be specially interested in) the science *per se*.

The adult public is very heterogeneous. All of us are part of it. Professional scientists are depressingly 'lay' outside their specialisms – I depend on 'popular' presentations in the media for updates on biomedical topics. Broadcasts or newspaper articles about my own professional interests deepen my respect for journalists who successfully cover all the sciences, working to tight deadlines. I know, from experience, how hard it is to explain non-technically, even something in my specialist field.

Science generally earns a newspaper headline, or a place on the TV bulletins, only as a background rather than as a story in its own right. Indeed, coverage restricted to 'newsworthy' items – newly announced results that carry a crisp and easily summarisable message – cannot avoid distorting how science develops. Scientists cannot reasonably complain about this any more than novelists or composers would complain that their new works do not make news bulletins. The place of science is in features, documentaries, and so forth rather than news.

A recent *Daily Telegraph* poll asked people on what topics they would like to see more newspaper coverage. Top choice was medicine; science and invention tied with crime for second place.

Within science, it is often the utterly 'irrelevant' subjects that fascinate people most. Dinosaurs have topped the charts since Richard Owen announced their discovery at the British Association in 1841. Cosmology runs dinosaurs close; so does human origins. Despite an intellectual climate where some scientific advances arouse unease, these subjects have retained a positive and non-threatening image.

Communicating science: a researcher's perspective

Researchers do not usually shoot directly for a grand goal. Unless they are geniuses (or unless they are cranks) they focus on 'bite sized' problems that seem timely and tractable. That is the methodology that pays off. However, it carries an occupational risk – we may forget that we are wearing blinkers and that our piecemeal efforts are only worthwhile insofar as they are steps towards some fundamental question. The physicist Arno Penzias, who made a really great discovery, said that he did not himself appreciate its full significance until he read a 'popular' description of it in the *New York Times*. Presenting our work as clearly as we can to general audiences, who do not care about the details, helps us to see it in perspective. (Niels Bohr said that you should speak as clearly as you think, but no more so. That is a good maxim – though Bohr himself apparently took caution to excess by mumbling inaudibly and incomprehensibly!)

Another salutory question for scientists is this: if you could inject one idea from your subject into 'common culture', what would it be? I should choose cosmic evolution.

At British Association meetings in the 1860s, Darwin's ideas were boisterously debated; they were part of the nineteenth century culture. He showed (to quote the famous final words of the 'Origin of species') how, 'whilst this planet has been cycling on according to the fixed law of gravity, from so simple a beginning, forms most wonderful... have been, and are being, evolved'. Cosmologists now go back before Darwin's 'simple beginning'. They view our entire solar system in a broad evo-

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lutionary context, stretching back to when the Milky Way galaxy first formed – right back, even to the hot dense fireball from which our entire universe emerged.

When a star explodes as a supernova, astronomers and physicists study it eagerly. Yet why should anyone else be interested in exploding stars thousands of light years away? The answer is that they hold the answer to the question 'where did the atoms we are made of come from?' Were it not for supernovae, none of us (nor even the earth) could exist.

Stars and nebulae contain roughly the same proportions of the different chemical elements as our solar system. What determines this universal mix? Did a creator turn 92 different knobs? The answer is no. Atoms on earth were forged by nuclear fusion in ancient stars that exploded as supernovae somewhere in the Milky Way. The atoms then found themselves in an interstellar cloud that condensed into new stars, some with retinues of planets. One of these stars was our sun. We can calculate the resultant 'mix' – why carbon and oxygen are common, but gold and uranium are rare. Galaxies are like vast ecosystems, in which pristine hydrogen is recycled through successive generations of stars, gradually building up the entire periodic table.

That link between us and the stars is just an example of the kind of concept that I should like to be part of the broader culture. It stimulates, of course, another question: where did the hydrogen itself come from? The answer itself lies in the initial big bang which set our entire universe expanding – another (more uncertain) story. However, it leads into my next topic, the scope and limits of science.

Hierarchy of sciences

Claims to understand anything about the early universe might seem presumptuous, but cosmology is actually one of the more tractable sciences. Inside a star (and in the early universe) conditions are so extreme that everything is broken down into its atomic constituents, and governed by simple laws. Moreover, the laws of physics are universal: atoms in remote galaxies and at early cosmic epochs obey the same laws as those we study in the laboratory. It is complexity that makes things hard to understand, not size. Understanding a frog is a far more daunting intellectual challenge than anything confronting cosmologists.

The atoms that made the young earth are stardust – to have understood this is a triumph of twentieth century science. However, elucidating how those atoms combined, via Darwinian selection, into progressively more intricate forms, and eventually into creatures that could ponder their origin, is an unending quest that has barely begun. This perspective should caution us against scientific triumphalism – against exaggerating how completely we will ever understand anything really complex. The different sciences are in a hierarchy – in the complexity of the things they deal with – with physics at the base and (I suppose) psychology at the apex. But that does not mean that the other sciences are applications of physics. Every science, from chemistry to social psychology, has its own irreducible concepts, based on the emergent properties of complex systems. In understanding turbulence, analysing the fluid in atoms does not help. What goes on in a computer could be described in electrical terms, but that misses the essence, the logic encoded in those signals. We cannot solve Schrödinger's equation for any biological system, but even if we could, it would never yield an economical description or insight.

There is a sense – but a limited one – in which some sciences can claim to be especially 'fundamental'. Causal chains – if you go on asking why? why? why? – lead back to a question in particle physics or cosmology. These subjects relate to deep aspects of reality. We pursue them for the stimulus they pose (to theorists and instrumental innovators alike), and because the breadth has proved a fruitful policy – not because the rest of science depends on them. The sciences are not in a hierarchy whose superstructure is imperilled by an insecure base.

Status of scientific ideas

The way we approach science, what problems strike us as interesting, what styles of explanation are culturally appealing, and (more mundanely) what fields attract funding depend on a range of political, sociological, and psychological factors. Some projects, especially big international ones, are a by-product of activities driven by other imperatives. (For example, the exploding supernovae I mentioned above would be less well understood were it not for the space programme, and supercomputers.)

It is important, as well as enlightening, to appreciate how pervasive these social and political factors are. The behaviour of scientists, and the external influences on their community, offer fascinating topics for study. However, for us 'in the zoo' science itself advances, albeit fitfully, towards a culture independent outcome. Steven Weinberg gives an apt metaphor:

> A party of mountain climbers may argue over the best path to the peak, and these arguments may be conditioned by the history and social structure of the expedition, but in the end either they find a good path to the summit, or they do not, and when they get there they know it.

Why can we, seemingly, make some sense of the external world? Why can so much be described mathematically? Is mathematics itself a discovery, or an invention? These questions are for philosophers – they are deeper than scientists can professionally address. So let us turn to more concrete aspects of discovery.

Discoveries out of the path of imagination

Nearly 400 years ago Francis Bacon highlighted three astonishing discoveries – gunpowder, silk and the mariner's compass. In '*Novum organum*' he writes: 'These things... were not discovered by philosophy or the arts of reason, but by chance and occasion'; they are 'different in kind so that no preconceived notion could possibly have conduced to their discovery'. It was Bacon's belief that 'there are still many things of excellent use stored up in the lap of nature having nothing in them kindred or parallel to that which is already discovered... lying quite out of the path of imagination'.

So it was, most certainly, in the nineteenth century. X-rays, discovered just 100 years ago, must have seemed fully as magical as the compass did to Bacon. Though of manifest benefit, they could not plausibly have been planned for. A proposal to make flesh appear transparent would not have got a research grant – even if it had, it surely would not have led to X-rays. It is easy to pick other examples. A nineteenth century project to reproduce music would have led to immensely elaborate pianolas or orchestrions, but would not have identified – still less accelerated – the technologies that actually achieved this goal.

Bacon contrasts his three 'magical' discoveries with the invention of printing, which 'has nothing in it which is not open and generally obvious... when it had been made, it seems incredible that it should have escaped notice so long'. Most innovations now emerge, as printing did, via Bacon's second route: 'from the transferring, composition and application of [things] already known'. What is remarkable, and indeed exhilarating, is that discoveries still take us unawares. There can still be scientific revolutions, despite the immense infrastructure of natural science that was quite lacking in Bacon's day, or even in the nineteenth century; indeed the lengthened frontiers of knowledge increase the chance of surprises.

I will focus below on some contemporary lessons that can be drawn from these distinctions, but will first make some general remarks on the creative impetus that drives any discovery or invention.

Creativity and individuality

Scientific insight needs concentrated effort and preparation. It also demands intuition and imagination. In this respect, it parallels artistic insight – equally an attempt to seek new patterns, and new perspectives on the world. However, those similarities should not obscure one glaring difference between the two enterprises, which stems from the interlocking, cumulative, and intensely social character of science.

In the arts, individuality shines through even at the amateur level. Everyone's contributions, even if soon forgotten, are personal and distinctive. Issues or priority do not arise, as they do in science. As Medawar noted, when Wagner took 10 years off in the middle of the Ring cycle to compose the '*Meistersinger*' and '*Tristan*', he was not worried that someone would scoop him on '*Götterdämmerung*'.

In science, discoveries emerge when the time is ripe – they are contingent on some prior innovation, perhaps in another field. Individuals seldom make more than a few years' difference to when a particular advance occurs. There are exceptions – the laser for instance, or sociobiology – but in populous fields the key ideas are 'in the air', ready to be grasped. The greatest figures may, however (as Watson and Crick, for instance, did) help those ideas to gell neatly, rather than emerge untidily. What made Einstein unique in twentieth century physics is that he really did make a distinctive long lasting imprint: without him, we might have had to wait decades for equivalent insights on gravity.

Although their personal imprint may fade, scientists have the compensation that, if it survives critical scrutiny, their work endures as a brick in the edifice of 'public knowledge'. And they have a second compensation: literary critics are seldom also creative writers, but every researcher is, albeit in a small way, both a creator and a critic of the collective scientific enterprise.

These remarks about science, incidentally, are intended to embrace engineering and technology as well. Claims that 'academic' research demands mental processes of a specially elevated kind are baseless snobbery, of a kind that is thankfully dying out. There is at least as much innovation in the computer or pharmaceutical industry as in any field of basic research. Indeed, the intellectual leap in the concept of a zip fastener surpasses what most academics achieve in a lifetime.

Until the nineteenth century academic science (such as it then was) was only tenuously linked with practical innovation. Science and technology now have a complex symbiosis. Research triggers applications; but, equally, new techniques and instruments boost scientific discovery. If you look at what people do day by day, there may seem little difference between a biotechnology company and a university laboratory, not between someone in an aerospace company and someone innovating an instrument for space astronomy. These activities have something crucial in common: the work is only worthwhile – it will only pay real 'dividends' – if it is really at the leading edge.

Forecasting and insight

In 1937 the American National Academy of Sciences organised a study aimed at predicting breakthroughs; its report makes salutory reading for technological forecasters today. It came up with some wise statements about agriculture, about synthetic gasolene, and synthetic rubber, but what is more remarkable is the things it missed. No nuclear energy, no antibiotics (though it was 8 years after Fleming), no jet aircraft, no rocketry nor any use of space, no computers; certainly no transistors. This committee overlooked the technologies that actually dominated the post-war era.

The pace of technological advance certainly is not slacking. Some everyday artefacts – laptop computers, camcorders, even supermarket barcodes – depend on basic science that dates back only 20 years or so. Likewise the new fields of biotechnology. A current attempt to predict future breakthroughs might have a 'hit rate' as dismal as the US forecasters achieved in 1937. The most dramatic and fruitful innovations will still surprise us. They will be the outcome of *some* new basic science, but of course we do not know what. Applications that are transforming the way we live were initiated by investments in basic research that were modest in relation to their impact. Some projects paid off colossally; others did not, but retrospective studies in the USA suggest that overall 'return' on basic research exceeds 20%.

On the football field, not everyone scores – you cannot predict who will, nor when. However, that does not mean that the other players are dispensable. Likewise, it is essential to maintain a broad science base, and a web of connections between different disciplines. Advances that deepen our understanding of some important aspects of nature – the physics of materials, living cells, or the environment – or even new mathematical ideas, are likely to find some application.

Obviously some fields are more likely to foster applications than others (I would concede that molecular biology is a better bet than black holes in this regard!), but 'curiosity driven' research can impact in quite unexpected ways. For instance, it was studies of dust in interstellar space that led to the carbon structures known as fullerenes; and the exotic fauna on the ocean bed may seem as remote as outer space, but their ecology is relevant to the Brent Spar debate.

Nothing I have said, incidentally, is meant to disparage the Foresight exercise undertaken by the UK Government, whose agenda is less futuristic. The Foresight panels bring people together, forge new links that are themselves worthwhile, and will help the country to exploit what has already been discovered. A 'Foresight' strategy could do harm only if undue concentration on highlighted research areas led to a funding blight on others.

Climate for invention and discovery

The UK has a fertile record for 'leading edge' discovery and invention. Can we enhance it – can we at least ensure that we do not slide relative to others? and can we exploit our discoveries better?

'A society organised to allow and celebrate the creative spirit of science will find itself also productive of the other forms of creativity which make life worth living. The societies where the bursts of scientific energy occur...span the other arts too.' This quotation is from a lecture given last year by William Waldegrave[1]; he went on to present a recipe, with which I strongly agree. We must reverse what he termed the 'Balkanisation of intellectual life – an affliction as acute in the humanities as in the sciences'. He recommended a broader education, interdisciplinary contacts in universities, and 'public understanding' programmes. However, current trends risk moving the other way – towards conditions *less* propitious for real innovative thinking, or for a more integrated culture.

The UK Government 1993 White Paper 'Realising our potential' rendered explicit the doctrine that science could be harnessed to wealth creation; and also to enhancing the quality of life. (Incidentally 'creating wealth' and 'enhancing the quality of life' are not really equivalent 'ends' that should be equally extolled. The Newcastle philosopher Mary Midgley, who writes cogently on such issues, reminds us that much economic activity is valued as a means, direct or indirect, towards enhancing activities that we undertake for their own sake.)

Most of us would broadly assent to what the White Paper's principal authors meant. Indeed there are echoes right back to Bacon: 'the emolument of life... and the relief of man's estate'. Yet some things being argued in its name risk being unwittingly detrimental to these shared aims. Unduly *dirigiste* policies would quench real originality. Not only would this be bad for basic research in itself, but it could compromise the research universities, whose standards are crucial for the quality of expertise entering industry and the professions, as well as the flow of new ideas – precisely the activities that have (in retrospect) been their prime contribution to the economy. (My biomedical colleagues may be more sanguine because they have more options for supplementing governmental funds from other sources.)

Budgetary competition is obviously acute – between science and other public spending, and among the sciences themselves – but efforts to make research more accountable and impose a business based perception of efficiency could backfire, for three reasons. First, assessment exercises, grant reviews, and so on can become so time consuming that they seriously erode effort. Second, the most original lines of inquiry cannot always be 'packaged' into acceptable research proposals. Third (and more insidiously) the most creative and astute individuals may be discouraged from pursuing a research career altogether. It is a poor deal if top quality innovative output falls by a bigger percentage than the financial 'saving'. We need to be businesslike. So does a hospital – so does even a church – but that does not mean that we should operate too like a business.

Despite Britain's poor showing in other international league tables, we certainly do not lag Germany and Japan in the quality and range of our discoveries. Nor do we lag economically in industries like pharmaceuticals, where the research emphasis is strong. The challenge is to remedy our relative weakness in other sectors without jeopardising what is already doing well. Scientists can be excused for thinking that the problem lies not primarily in themselves, but in the low research and development investment in some sectors, and companies that are not even receptive customers for research or enlightened employers of scientists.

Because the universities and research councils are public bodies, the government has been able to enhance the industrial influence on them. What is lacking is enough diffusion the other way. Perhaps we need to match Germany and Japan in the number of scientists and technologists on company boards.

An international opportunity

It is not only in Britain that mechanisms introduced to make research more efficient risk backfiring. A survey by the physicist Leon Lederman, when he was AAAS President, revealed how young US scientists perceived their prospects and pressures as being worse than their predecessors'.

Despite its alleged malaise, US science maintains great vitality. This is because its catchment area for talent extends worldwide. The USA is a magnet for the strongest graduate students and researchers. These come especially from Asia, but from Europe as well. (After the collapse of the Soviet Union, many leading Russian scientists moved directly to the USA.)

Why should we not try to match the blandishments of the USA for internationally mobile talent? All too often, one hears of people being 'lured abroad', as though this drain is something we must resignedly accept. Yet, this country has impressive advantages through the quality and tradition of our best research institutions, and we have an unmerited headstart over our European neighbours through the primacy of the English language.

UK universities have a fine record for attracting overseas students, but we should surely press it further. Why not aim to be the country of choice not only for undergraduates, but for top ranking graduates, and for the potential leaders of the international research community – those whose first instinct is now to go the USA? Everyone is aware of the benefits of the right kind of inward investment. Britain could surely exploit more fully its manifest comparative advantage as a magnet for talent, a location for research centres, and an incubator for discovery and invention. The law of increasing returns surely applies: an extra 5% funding would yield much more than a 5% boost. Conspicuous success feeds on itself by stimulating and drawing in more expertise. As one of the 'societies where bursts of scientific energy occur' – to quote William Waldegrave's words again – we would gain all the correlated benefits that he identified.

Young people: the 16–18 curriculum

This leads to the worrying issue of school education, where our international rankings are low. My remarks above on 'public understanding' omitted one specially crucial segment of the 'public': those still in school. The British Association runs programmes, all through the year, to build on young people's natural enthusiasm for science and technology. It is keen to foster and cooperate with innovative schemes that bring individual research scientists in contact with schools. There is growing scope here: telecommunications allow remote access to large facilities, so that individuals – amateurs at home, as well as young people in schools – can participate in scientific discovery. Future scientists may be less corralled into large laboratories.

Sir Claus Moser's Presidential Address in 1990 led to the National Commission on Education, run under the association's auspices and funded by the Hamlyn Foundation. There have been moves towards implementing a few of the commission's recommendations – on nursery education, and on coordinating vocational qualification – but there has been little movement on most others. Sir Ron Dearing is now reviewing the system of qualifications at 16 and 18; we hope he will interpret his remit broadly, and note the commission's strong emphasis on broadening the A level curriculum.

Young people opting for humanities should not drop all science when they are 16. An appreciation of science is vital not just for tomorrow's scientists and engineers, but for everyone who will live and work in a world underpinned by technology – and even more vulnerable to its failures and misapplications than the present one. Even more important, the option of higher education in science and technology should not be foreclosed to them. (These concerns pertain to England more than Scotland. Scottish education has its admirers here, but few in Scotland advocate a switch to the English system?)

It is crucial that enough of the brightest young people go on to acquire some professional expertise in science and technology. They will not do so unless, when making the key decisions at age 16 or 18, they perceive a range of appealing opportunities. They will be discouraged if the courses do not inspire them; or if the exciting discoveries reported in the media all seem made in the USA (or, worse still, by people from this country who have defected overseas). They will be discouraged if scientists seem valued less than accountants; and they need to feel that science is humanly relevant – that it meets their ethical concerns.

The OST and the DTI

A word now on the recent reorganisation of government science in Britain. The science, engineering, and technology community broadly welcomed the setting up of the Office of Science and Technology (OST) in the Cabinet Office. William Waldegrave, as its first minister, gained wide respect for his genuine commitment. We in the British Association especially appreciate the OST's continuing support for our mission of enhancing public understanding of science.

The shift into the Department of Trade and Industry (DTI) surprised most of us. It seemed to reverse one of the few government initiatives of recent years that commanded genuine bipartisan support. There had been no overt pressure for the move, certainly no open discussion. Some industrialists (Sir Richard Sykes among them) have argued that from their perspective, and that of smaller companies, the change could offer benefits. We hope the move indeed proves beneficial, but it would be remiss not to mention the worries some association members have, in the hope that they will prove groundless.

There is concern that there should not be an undue focus on research with a short term payoff – this is not just because we value curiosity driven research for its own sake (though we do), but because past experience suggests that it is through free ranging basic research that the universities can make their most distinctive contribution to boosting industry and meeting other public demands.

There is also concern that its embedding within DTI should not hamper the OST's efforts at deploying the overall case for science, and coordinating policy across other departments. Strong links are indeed needed with industry, but it is also important to strengthen those with defence, health, environment, and (perhaps above all) with education. And the new Chief Scientific Adviser must have a real cross-departmental influence – Professor May, an old friend of the British Association, carries with him our good wishes and confident hopes. Also the Commons Select Committee should continue – it is an index of parliamentary interest in scientific and technical matters.

Science is not a monolithic profession; not a single constituency; certainly not a lobby. It is a pervasive activity. As with other long term issues (energy and environment, for instance), it is best if national science policy is bipartisan, rather than the subject of strident debate. However, the 'downside' is that science then loses visibility on the political agenda. The British Association, with its broad involvement, and its traditions as an informal 'parliament of science', is well placed to extend its role as a policy forum; I think it has a responsibility to do so. Let us hope that long term issues will generally loom larger as the millennium approaches.

The atomic scientists

I should like to devote a few final comments to broader (even global) issues of scientific concern. We have recently marked the anniversary of the atomic bomb – an invention as 'different in kind' from anything before as gunpowder seemed to Bacon.

Many physicists who had worked at Los Alamos during the war returned to academic work straight afterwards. Some of them founded the *Bulletin of Atomic Scientists*, a journal with the aim of alerting the world to the dangers of an arms race, and the urgency of arms control. The cover page of each issue shows a clock, the closeness of whose hands to midnight indicates how precarious the world situation is (or is thought to be by the journal's Editorial Board).

At the time of the Cuba crisis, the clock was at only 3 or 4 minutes to midnight. It was there again in the mid 1980s. At that time, the main issues were how to reduce the ever present risk of escalation towards catastrophic nuclear war – by malfunction or miscalculation, even if not by premeditated strategy. The risk in a single year may have been small, but the probability would have mounted up if conditions had not changed.

The nuclear arms race, from the 1950s to the 1980s, was fuelled not only by misdirected resources, but by misdirected inventiveness. Virtually every innovation was quickly matched by the other side, and the arsenals ratcheted upwards. Yet throughout this time some scientists (the founders of the *Bulletin* being among them) were using their international influence to foster arms control. In particular, there was constructive dialogue at the 'Pugwash' conferences, named after the village in Nova Scotia where the first meeting was held. The physicists involved in such conferences were in numerical terms trivial compared with those in weapons laboratories, but they constituted an informal channel back to their governments, and were genuinely influential in instigating formal contacts – especially in the 1960s, before other Each–West channels opened up.

Scientific input into policy: the transatlantic contrast

From the 1970s, scientists from a younger (post-war) generation became active in arms control debates; some of these went on to hold official posts, either in the USA or in Russia. However, such people have no real counterparts in the UK, where we still rely on independent voices from the Second World War generation, who have maintained their concern ever since.

The reasons for this transatlantic contrast are not hard to find. In the USA, there is a 'revolving door' between government jobs and universities (or organisations like the Brookings Institute) whenever the administration changes. The American Physical Society, the Union of Concerned Scientists, and other organisations, can draw on this independent expertise to prepare (often influential) reports. There is also the Jason Group – physicists of the highest academic repute who meet regularly, for several weeks per year, bringing fresh minds to bear on issues relevant to the Defense Department. Jason Group reports are generally classified, but its members acquire a background and credibility that enhances their effectiveness in open discussion.

Over here, on the other hand, government science is generally a lifetime career. The more pervasive secrecy inhibits well informed open debate. Defence scientists form a rather closed world. My own experience illustrates this. I have had contact with many physicists from Los Alomos and Livermore (who attend academic conferences, and contribute to the open literature), but not with their British counterparts. Greater openness could actually strengthen the defence establishments themselves. Their primary activities will (one hopes) be throttled down, but they must be helped to retain wide competence; arms control and verification will demand innovative ideas in many fields (chemical and biological, as well as physics based areas like space technology).

These specific points about defence science are a symptom of something that is routinely deplored at British Association meetings – the meagre input of scientists into the general political process in this country. This precludes informed debate on technical issues where well thought out new ideas are needed – energy, environment, and transport policy, as well as defence. We could learn from US practice and set up 'Jason style' groups – leading scientists from academe or industry who would not merely sit on advisory committees, but commit themselves to carry out serious interdisciplinary studies. This is something the new Chief Scientific Adviser might consider; or else an independent foundation.

Another valuable innovation would be a forum or institution that could fulfil, in the scientific and technical arena, the role that Chatham House fulfils in foreign policy. This is something that the British Association itself, perhaps with partner organisations, could seek to implement.

Global risks

The clock on the *Bulletin's* cover has been put back to 17 minutes to midnight. In nuclear terms, the world seems on a longer fuse, but bewildering new risks now confront us. These may not threaten a sudden worldwide catastrophe – the doomsday clock is now a less good metaphor – but are, in aggregate, as worrying and challenging.

The nuclear arsenals must be safeguarded, and gradually dismantled. Nor must new weapons proliferate, of types that require only minor adaptations of legitimate technologies that every nation aspires to.

For most of the world's people, the ideological stances of East and West were always an irrelevant distraction from the immediate problems of poverty, and natural hazard. These 'threats without enemies' relate to global questions of environment, resources, and biodiversity: how can these be safeguarded without jeopardising the aspirations of the poorer nations? There is no case for a brake on technical advances – the need, rather, is to accelerate but redirect them.

The thrust of economic development must, urgently, shift towards a mode that is more equitable, environmentally benign, and sustainable. This was a theme of Dr Anne McLaren's Presidential Lecture last year. She reminded us that education (especially for women) is a priority worldwide, not only for its own sake but because of its impact on family size. Stemming population growth may be a prerequisite for attaining acceptable quality of life everywhere.

I should like to quote related sentiments from a different quarter, the Prince of Wales. In a lecture at Cambridge University, he said:

> The strategic threats posed by global environment and development problems are

> the most complex, interwoven, and potentially devastating of all the challenges to our security... Scientists... do not fully understand the consequences of our many faceted assault on the interwoven fabric of atmosphere, water, land, and life in all its biological diversity. Things could turn out to be worse than the current scientific best guess. In military affairs, policy has long been based on the dictum that we should be prepared for the worst case. Why should it be so different when the security is that of the planet and our long term future?

When the risks are global, the obligation to inform and to seek solutions extends to the international scientific community. Current concerns are much more diverse than those of the Cold War era, and cannot be tackled without wider expertise. Scientists in this country might have been reluctant to dedicate their energies to *nuclear* arms control issues – in the 'superpower' confrontation, nothing Britain said seemed to count for much – but now that the agenda has changed, there need be no such inhibition. Britain has impressive credentials and a high international profile in the broad range of expertise that these global problems entail – problems that should loom as large in the political agenda as did the East–West political divide in the Cold War era.

Conclusion

I shall close with another brief cosmic perspective. Planets like ours – 'cycling on', in Darwin's words, 'according to the fixed law of gravity' – are surely very common in the universe. But those that harbour such *complexity* as ours could be surpassingly rare. The intricate biosphere, of which we are part, has taken several billion years to evolve, but in terms of cosmic timespans, we are not yet at the halfway stage – we could still be nearer to Darwin's 'simple beginning' than to the endpoint of the evolutionary process.

It is, primarily, collective human actions that will determine how, or even if, that process unfolds. Being mindful of these potentialities stretches our horizons: it should deepen our commitment to understand our world, and conserve its web of life.

Literature cited

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