Science forecasting: predicting the unpredictable

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Abstract
Standard methods for forecasting future developments in technology are based on extrapolating current trends. A weakness of such methods is that they cannot predict the impact of major breakthroughs or 'revolutions' in basic science that might lead to radically new technology and a fundamental change in the way wars are fought. While such revolutions cannot, by definition, be predicted in any detail, it is possible to identify many of the broad factors that are involved in turning scientific breakthroughs into feasible technology. This paper reviews a number of historical examples where new technology has arisen out of revolutionary changes in science, and analyses the process by which such revolutions occur. There can be little doubt that further scientific revolutions will occur and any defence planning that looks more than 15 to 20 years ahead must be flexible enough to take account of the potential disruption caused by the radically new technologies that might emerge as a consequence.

1 INTRODUCTION

Accurate technology forecasting is important to anyone who has a financial or professional stake in the future, from individuals and small businesses to governments and multi-national corporations. Ministry of Defence funds for basic research are limited; it is therefore important to target these funds so that the UK does not fall behind in emerging areas of military relevance.

The commonest methods used in technology forecasting are based on mathematical extrapolation of current trends (for example, using exponential or logistic curves), but these can only represent evolutionary development of existing technology [1, 2]. The worrying possibility is that such techniques will fail to predict revolutionary changes in technology that might result in a large-scale upheaval in the way wars are planned and fought. Such 'disruptive technology' often emerges following a major breakthrough in fundamental science. Predicting the impact of such breakthroughs (*science forecasting* as opposed to technology forecasting) is the subject of this paper.

Section 2 reviews some historical examples of the technological exploitation of new science, including a few failures as well as many notable successes, to identify the key factors involved. Section 3 then looks at the mechanisms by which new scientific breakthroughs occur, and section 4 asks the question "What will the next breakthrough be?" The all-important next step - turning the new science into effective and usable technology - is the subject of section 5. Finally, section 6 summarizes the conclusions that can be drawn on the extent to which radical developments in future science can be anticipated and planned for.

2 HISTORICAL REVIEW

Some successes

The atom bomb is perhaps the most famous (or notorious) example of military technology emerging from developments in fundamental science. This example is particularly remarkable for the speed with which it was developed. The ability to transmute one element into another was first demonstrated in the laboratory by Rutherford in 1919, and the practicality of a fission chain reaction was established theoretically less than 20 years later. Enriched uranium and plutonium were first made in 1940. The Manhattan project was set up in August 1942, and the first bomb was tested successfully in July 1945, just under three years later.

What made it possible to develop the atom bomb so quickly? Obviously, one reason was that there was perceived to be a pressing military need for it, so there were few financial or political obstacles to contend with. Secondly, the biggest hurdles were in understanding the basic physics and acquiring the raw materials; once these were overcome, it was relatively plain sailing to develop a first-generation weapon.

The other military application of atomic physics is the nuclear submarine, which was also a rapid development. The USS Nautilus was launched in February 1953, just over ten years after the first controlled nuclear reaction in December 1942.

Atom bombs and nuclear submarines illustrate the speed with which discoveries in fundamental science can be turned into practical technology. A good counter-example is the gyroscope. This is a very straightforward mechanical device, the physics of which is entirely contained within Newton's second law of motion, first published in the mid-17th century. Yet it was two hundred years before Foucault first demonstrated the principle in a laboratory, while the first practical application, Sperry's gyrocompass, had to wait until 1911. Engineering difficulties notwithstanding, the most important factor here may simply have been that the gyroscope was an invention waiting for an application. It was not until the advent of submarines, torpedoes, aircraft and missiles that the market pull was strong enough to drive its development.

As an aside, it is remarkable that, as a 19th century invention based on 17th century science, "gyroscope" was still considered a high-tech buzzword in the science fiction of the 1930s, 40s and even later. During World War 2, British scientists were at

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a loss to understand how the Germans achieved accurate targeting of their V-2 rockets until Technical Intelligence informed them that gyroscopes were used [3].

The twentieth century offers many other examples of successful military technology emerging from recent advances in science. Some of the highlights are:

- **Radar.** The physics of radar is contained in Maxwell's equations, which were published in the 1870s. Hertz first produced radio waves in 1887, and the idea that they could be used for the detection and ranging of objects was suggested by Tesla as early as 1900 (and described graphically in a science fiction novel by Hugo Gernsback in 1911). Superheterodyne radio was invented in 1918, and the magnetron in 1920. Radar was developed independently in several different countries during the 1930s, and effective microwave radars came into service during WWII.

- **Lasers.** The physics of stimulated emission was described by Einstein in 1916. There is no obvious reason why the first lasers could not have been constructed fairly quickly after that, but in fact they weren't. The reason may be that (unlike radar) there was no obvious application to drive their development. Historically, lasers were preceded by their microwave equivalent, masers, developed in the 1950s on the back of radar research. The first lasers followed early in the 60s, and very rapidly saw application in Paveway guided bombs as early as 1965.

- **SQUIDs** (Superconducting Quantum Interference Devices). Superconductivity was first observed in the laboratory in 1911, and an explanation of the effect in terms of quantum physics was gradually developed over the next 50 years. The Josephson effect was described in 1964, and the first SQUID based on this effect was constructed in 1967. SQUIDs can be used to detect extremely small magnetic fields, though as yet magnetometers using this technology are still at the research stage. High-temperature (> 77K) superconductors were discovered in 1986, vastly reducing the cost of the cryogenic systems required, but the problems of motion noise still need to be solved before a sensor robust enough for military applications can be built.

- **Microchips.** The basic physics of semiconductors was understood by the late 1930s, building on discoveries in atomic structure over the previous two decades. The first transistor was constructed in 1947 and, by the 1950s, solid-state components were replacing vacuum tubes in most electronic devices. The first integrated circuit followed in 1959, and within twenty years it was possible to fabricate single chips containing hundreds of thousands of components. This paved the way for the current revolution in computing, information technology and the internet.

Some failures

Not all attempts at technological exploitation of new science have been successful. Around the same time that the US Navy started thinking about nuclear-powered submarines, the US Air Force began the development of a nuclear-powered aircraft [4]. During the 1950s, almost a billion dollars was sunk into the project before it was finally cancelled in 1961. Many of the problems were technical (such as the enormous weight penalty associated with effective radiation shielding) but the concept also suffered because there was no unequivocal military need for it. Ballistic missiles could deliver warheads equal distances with less danger of interception.

Even when a technology is scientifically feasible, there needs to be a demand for it before expenditure on its development can be justified. An example is hypersonic (> Mach 4) air vehicles. While such vehicles pose many technical problems in propulsion, aerodynamics and materials, these do not seem to be insurmountable, and with adequate funding hypersonic missiles, aircraft and reusable single-stage-to-orbit space launchers could by now have been in widespread use. As it is, the main thrust of technology has developed in different directions (ballistic missiles, stealth aircraft and multi-stage satellite launch rockets) and, while hypersonics has received on-and-off attention over the last fifty years, it still remains to be exploited fully.

On other occasions, seemingly spectacular scientific breakthroughs may fail to stand up to closer examination by the engineering community. Following the demise of the Soviet Union, several Russian groups (motivated, a cynic might suppose, by the lure of Western currency) came out with extravagant claims concerning apparently new scientific phenomena. Amongst these was the assertion that massive reductions in aerodynamic drag could be achieved by enveloping an aircraft in a weakly ionized non-equilibrium plasma - an effect that the Russians ascribed to novel facets of plasma physics unknown in the West. However, exhaustive tests carried out by DERA (in collaboration with some of the Russians themselves) eventually brought the claims down to earth. The experimental results can all be explained by known physics (heat addition), and the spectacular drag reductions are only obtained for unaerodynamic shapes like spheres. The effects on realistic aircraft shapes are much more modest, and even then a plasma is not the most efficient way of achieving the required heat input [5].

Learning from history

Can historical examples like those described above help us to predict what may happen in future? Based on these examples, table 1 summarizes the key factors and time-scales involved in turning new science into useful technology. It is a fairly safe assumption that at least some of these patterns will repeat themselves in the future.

What scientific breakthroughs and new technology does the future hold? The film *Star Trek VIII: First Contact* portrays the invention of the warp drive as occurring in the latter part of the 21st century, some 200 years before the first voyage of the starship Enterprise. When *Star Trek* first appeared in 1966, the concept of warp drive was pure fiction. However, in 1994 theoretical physicist (and science fiction fan) Dr Miguel Alcubierre published a paper in the journal *Classical and Quantum Gravity* entitled "The warp-drive: hyper-fast travel within General Relativity" [6]. This presents a self-consistent solution of Einstein's equation, which in principle permits faster-than-light travel by locally distorting a bubble of space around

Table 1
Time-scales for developing technology from science

Technology	Time-scale	Factors
Atom bomb	25 years	High perceived urgency; few political/financial constraints
Gyroscope	250 years	No real application in early years
Radar	50 years	More than one enabling technology needed developing
Laser	50 years	Applications slow to be recognized
SQUID	30 years	Required both theoretical and experimental breakthroughs
Microchip	40 years	Manufacturing and reliability
Nuclear aircraft	unexploited	Huge engineering obstacles
Hypersonics	unexploited	Little requirement pull
Plasma aerodynamics	unexploited	Specious science

the spacecraft. Alcubierre's concept was a mathematical showpiece only, impossible from an engineering point of view (involving energies greater than the total energy of the universe and walls thinner than subatomic particles). However, subsequent refinements to the theory are progressing towards a more practical solution [7].

Science never stands still, and warp drive is just one possible technology that may emerge. The remainder of this paper looks in more detail at the various mechanisms involved, from basic scientific research to the successful exploitation of new technology.

3 HOW DO SCIENTIFIC BREAKTHROUGHS HAPPEN?

Kuhn's theory of paradigms

Thomas Kuhn's *The Structure of Scientific Revolutions* [8] is the definitive work on the way science makes progress. Kuhn's fundamental thesis is that the overwhelming majority of all scientific endeavour is fundamentally conservative and resistant to change. At any given time, all the major parameters of a particular field will be laid out in a standard textbook (real or notional), which Kuhn refers to as a "paradigm". The paradigm will allow room for numerous clarifications and refinements, and it is on such "fine-tuning" of the paradigm that most scientists are employed. The individual scientist, his university professors, his colleagues and his counterparts overseas all work within the same basic framework of accepted "truth", and see their role as building on this framework rather than shattering it.

Although the history of science is full of revolutions, scientists do not expect them or look for them (by definition – because the revolution involves the overthrow of the paradigm that represents the scientist's concept of 'truth'). This is not a criticism of scientists - good everyday science would be impossible without the supporting structure of the paradigm. In Kuhn's words, "Normal science, the activity in which most scientists inevitably spend almost all their time, is predicated on the assumption that the scientific community knows what the world is like. Much of the success of the enterprise derives from the community's willingness to defend that assumption, if necessary at considerable cost. Normal science, for example, often suppresses fundamental novelties because they are necessarily subversive of its basic commitments." It is only when overwhelming evidence has built up that scientists relinquish their belief in the old paradigm and a revolution occurs. Kuhn's phrase "paradigm shift" has entered the language, even among people who have no idea what it means!

To a scientist, Kuhn's ideas may seem harsh, and the immediate temptation is to dismiss them as irrelevant. But think - did textbooks of the late 19th century contain the slightest hint of atomic physics, quantum mechanics or superconductivity? And if the textbooks did contain the germ of a revolution (as in the case of Special Relativity, which is implicit in Maxwell's equations), how many blind eyes were turned to it before additional evidence mounted up? If DERA had been around 100 years ago, how many of its staff would have been comfortable with the idea of magnetism as a four-dimensional space-time transformation of an electric field? Experts are not always the best people to predict even the near-term future, as table 2 shows!

Table 2
Experts are not always good at predicting the future!

> *"In a few years all the great physical constants will have been approximately estimated, and the only occupation which will then be left to men of science will be to carry out those measurements to another place of decimals."* James Clerk Maxwell (Cavendish Professor of Physics, University of Cambridge), 1871.
>
> *"Heavier than air flying machines are impossible."* Lord Kelvin (President of the Royal Society), 1895.
>
> *"Airplanes are interesting toys but of no military value."* Marechal Ferdinand Foch (Professor of Strategy at the École Supérieure de Guerre).
>
> *"The idea that cavalry will be replaced by these iron coaches is absurd. It is little short of treasonous."* ADC to Field Marshal Haig at a tank demonstration, 1916
>
> *"There is no likelihood man can ever tap the power of the atom."* Robert Millikan (Nobel prize-winning physicist), 1923.
>
> *"The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine."* Lord Rutherford (first person to split the atom), 1933.
>
> *"While theoretically and technically television may be feasible, commercially and financially I consider it an impossibility, a development of which we need waste little time dreaming."* Lee DeForest (inventor of the vacuum tube), 1926.

Present-day paradigms

An impressive range of top-quality science is being carried out within present-day paradigms, in areas as diverse as subatomic physics, nuclear fusion, turbulence, neurobiology, climatology, molecular biology and complexity theory [9]. But while such research may push on the boundaries of the paradigm, it is basically evolutionary rather than revolutionary.

The last major paradigm shifts occurred more than fifty years ago, in the first half of the twentieth century. The lack of major change since then has created the illusion that such change is neither possible nor necessary. In physics, for example, undergraduates today are taught essentially the same syllabus that their professors were taught a generation earlier, possibly even using the same textbooks. To this extent, science has become a victim of its own success, and Kuhn's views on the conservatism of the scientific establishment are at least as true now as they were when he formulated them 40 years ago.

While a strong belief in the current paradigm is an important requisite for everyday science, there is the danger that, if it goes unchallenged for long enough, it can turn into fervour of near-religious proportions. The result is vicious scepticism and intolerance directed at any theory or observation that lies outside the paradigm. Currently, a favourite target is any suggestion that the force of gravity might be subject to technological modification. Yet a hundred and fifty years ago, no less a figure than Michael Faraday conducted a series of experiments on exactly this topic. Faraday was able to get away with such heresy because he had already made his reputation on electricity and magnetism. But history might have been quite different if events had happened in a different order [9].

4 WHAT WILL THE NEXT BREAKTHROUGH BE?

Some unsolved problems

Despite the successes of the current scientific paradigm, there are enough loose ends lying around to convince all but the most hardened sceptic that revolutions lie ahead.

- Fundamental physics is full to overflowing with arbitrary parameters – but where do they come from, and why do they manifest in the way they do? What is electric charge? What causes inertia?

- Quantum theory and General Relativity are incompatible with each other. Is there a missing theory – unified field theory, quantum gravity, M-theory or whatever – that will replace both?

- What is time, and why does it always advance at a constant rate? Why are some parts of physics time-reversible while others are not? Why is the time dimension of space-time perceived so differently from the spatial dimensions?

- Most physicists have brains (some have very effective ones), and presumably they experience things like consciousness, creativity and dreams. But if they didn't experience these phenomena for themselves, and only heard non-scientists' descriptions of them, would they dismiss them as mystical nonsense because they don't fit their paradigm?

- On all scales from the local solar neighbourhood, through galactic rotation curves, to groups and clusters of galaxies, the matter that can be observed through telescopes is inadequate (by a factor of up to 10) to explain the observed kinematics using Newton's laws of motion. The standard answer to this problem is to invoke some unknown form of 'dark matter'. In other words, scientists would rather imagine there to be ten times as much matter in the universe than they can see, than that their theory of motion might be wrong!

Some current research

There is no shortage of radical ideas on 'new' science. Unfortunately, most come from enthusiastic laymen who would have difficulty articulating Newton's second law of motion, let alone quantum physics or general relativity. These ideas are almost invariably based on faulty assumptions, specious reasoning, or badly-controlled experiments. It is largely because of such easy targets that the scientific establishment is so sceptical of new ideas. Yet there is a small core of reputable scientists who are genuinely interested in expanding the boundaries of their subject: some are respectable academics who made a name for themselves in a traditional field before turning to more radical topics; others are established players in the defence sector. All the examples in the following (non-exhaustive) list fall in one or both of these categories.

- **Unified field theories.** In 1990, a report was produced for the US Air Force entitled "Electric Propulsion Study" [11]. This reviews five-dimensional general relativistic theories that incorporate both electromagnetism and gravity, and proposes experiments to test the theories and serve as a basis for electric propulsive systems that would convert between electromagnetic and inertial momentum. Some of the work referred to was done by Dr Pharis Williams [12], who has collaborated with DERA on unrelated research.

- **Zero-Point Field (ZPF).** The ZPF is associated with the quantum-mechanical concept of vacuum fluctuations, ie, the idea that empty space is a sea of short-lived virtual particles permitted by the uncertainty principle. In a paper published in 1994 [13], Haisch, Rueda and Puthoff explain the origin of both gravity and inertia in terms of forces arising naturally from the ZPF. This theory holds out the intriguing possibility that the inertia of a body could be reduced or even neutralized by technological means. Experiments to test this possibility are described in a paper commissioned by the US Air Force [14].

- **NASA Breakthrough Propulsion Physics (BPP).** NASA is sponsoring research in fundamental physics that could potentially be turned into novel space propulsion technology, in particular focusing on the areas of reduced propellant mass, increased transit speed and compact energy sources [15]. Several of the BPP projects involve research in the areas of general relativity and the zero-point field.

- **BAE SYSTEMS Project Greenglow**. Within the UK, the closest equivalent to the NASA BPP project is a BAE SYSTEMS initiative called Project Greenglow [16]. BAE are investing a modest sum per annum into academic research in theoretical physics that might have aerospace implications. The universities involved include Sheffield, Lancaster, Birmingham and Dundee.

- **Gravitational effects in superconductors.** General relativity admits of other gravitational effects besides the familiar Newtonian law of gravity. For example, there is a gravimagnetic field associated with a moving mass, analogous to the magnetic field of a moving charge. Under normal circumstances, this field is unmeasurably small, because the gravimagnetic permeability of free space is minuscule. However, theoretical studies by Ning Li at the University of Alabama in Huntsville [17] suggest that under certain circumstances the gravitational permeability may become very large inside superconductors, leading to the possibility of a 'gravity shielding' effect. Experimental verification of this theory has been reported [18], although it remains highly controversial.

- **Scalar waves.** After anti-gravity, one of the favourite topics of conspiracy theorists is the 'death ray' or beam weapon. Claims about such weapons have been circulating for almost a century, often associated with the name of Nikola Tesla. The Journal of Defence Science published a review of the subject in 1997 [19]. Despite the emergence of lasers, microwave directed-energy weapons, and Ronald Reagan's Star Wars particle beams, none of these seems to match the characteristics of Tesla's ray. There is some evidence that Tesla technology is based on 'scalar waves' or manipulation of the magnetic vector potential, and that it is being actively developed in the former Soviet Union [20].

- **Water memory.** The French scientist Jacques Benveniste [21] has reported a series of experiments in which water appears to retain the molecular vibrational signature of dissolved chemicals that are no longer physically present (as in homeopathy). In related experiments, digital recordings have been made of the energy spectrum of molecules such as anticoagulants, transmitted over the internet from one continent to another, and played back to samples of pure water that then take on the biochemical properties of the original molecule. These effects may be related to the theory of living organisms as macroscopic quantum systems [22], proposed to explain electrical hypersensitivity. According to this theory, biology has more to do with vibrational energy states than with chemicals.

- **ESP.** If gravity control and beam weapons are guaranteed to raise the blood pressure of the average scientist, they are nothing compared with Extra-Sensory Perception (ESP) and related paranormal phenomena. Yet it is well known that the CIA and other intelligence organizations employed 'remote viewing' during the Cold War, with many apparent successes. Even in the UK, some professional scientists are open to the investigation of the subject [23], most notable among them being the Nobel prize-winning physicist Brian Josephson [24].

5 TURNING NEW SCIENCE INTO TECHNOLOGY

Factors affecting technological development

The aim of this paper is not to speculate on the likelihood of any particular scientific breakthrough occurring in the near future but to assess the impact of such a breakthrough, if it should occur, on the pattern of technological progress. What new technologies may emerge, and how quickly? As seen from the historical survey of section 2, the answers to these questions depend on the combination of many factors. These include:

- First and foremost, there must be a clearly perceived *requirement* for the technology, whether this is military or commercial (or both). Without such a requirement, it is unreasonable to expect adequate financial commitment by government and/or private investors to realize the technology.

- Secondly, the new technology must be based on science that is valid (and perceived to be valid), and its potential must be recognized both at the technical and decision-making level. If the new development is based on a paradigm shift, it will inevitably be extremely hard to convince potential financiers that they are not being asked to pay for science fiction.

- Development of the technology must be feasible on a time-scale that will repay the initial investment. This means that not only the basic design but also all enabling technologies and manufacturing processes must be feasible. The new equipment must be robust enough for service, and compatible with any other systems into which it will be integrated.

- The new technology must offer significant improvements in cost-effectiveness when compared with other means of achieving the same ends (for example, an anti-gravity aircraft may sound like a good idea but, if it turned out to require several multi-megawatt gas turbine generators to power the gravity shields, it would look no more attractive than a conventional jet aircraft). Cost-effectiveness estimates should take the entire value chain into account, including R&D, raw materials, manufacturing facilities, sales and marketing, regulatory aspects (international standards, health and safety certification, etc), running costs, maintenance and disposal.

- Finally, and particularly in the defence sector, it is important to consider issues of political acceptability. Even if a new technology is desirable, feasible and cost-effective, politicians may decide to ban it. There may be a good reason for this (for example environmental considerations, or the dangers of proliferation or an escalating arms war); but also there may not be - it is a lot easier to ban a new type of weapon than one that is already well-established and widespread.

Streamlining the process

The process of turning new ideas into marketable products and services, commonly termed *innovation*, is a keystone of modern economic theory [25]. Around the world, governments and corporations are keen to find ways of facilitating and speeding up this process, for obvious reasons - it is (or should be, if done correctly) a fast route to wealth creation, employment growth and improvements in the quality of life. In a drive to create an innovation culture, there is an increasing tendency for government policy to emphasize technology transfer and diffusion, for example through increased industry/public sector cooperation, and the fostering of venture-capital funded small/medium enterprises [26].

As a consequence, there is now an unparalleled opportunity for the rapid development and transfer to market of new technology. The danger, however, is that in emphasizing the downstream end of the technological value chain, there will be insufficient attention paid to the fundamental research and creativity needed to feed it with raw material. Radical innovations, as opposed to merely incremental ones, require investment at the level of fundamental science, as the examples of the previous sections have shown.

There are at least two reasons why investment in basic science may not be seen as the most attractive target for public funding. For one thing, the time interval between fundamental discoveries and ultimate in-service dates is normally much longer than the political time-horizon of five years. Secondly, the difficulty of keeping fundamental developments secret for any length of time means that there is no guarantee that the military or economic benefits will be the sole preserve of one's own country (consider the example of the information revolution, where Third World countries are benefiting at least as much as the United States and Europe). It is important that perceptual hurdles such as these are overcome if adequate funding is to be available for basic scientific research.

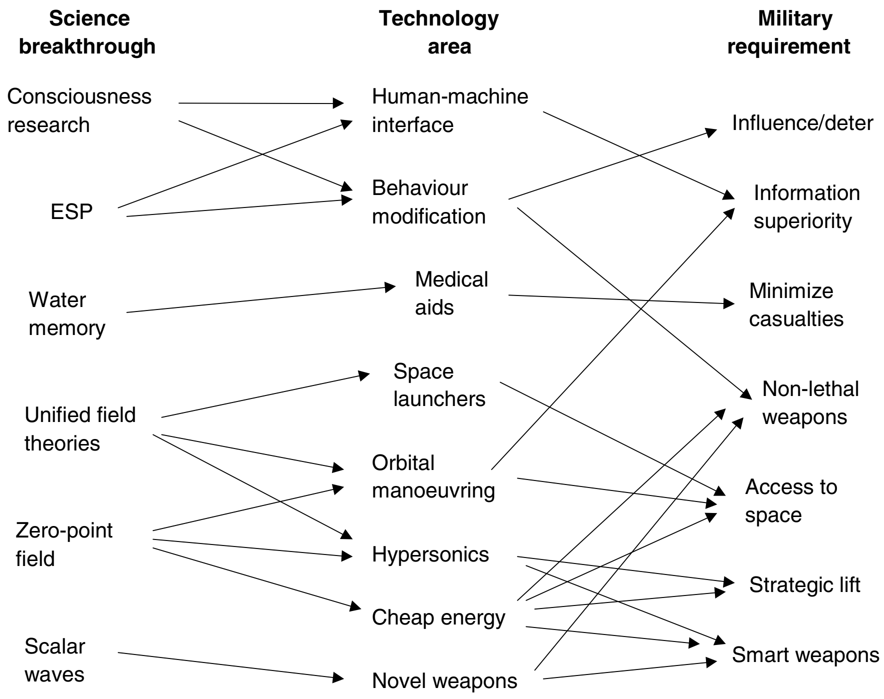

Fig 1. Scientific breakthroughs will lead to new technology to meet defence requirements

Putting the new technology into service

If we assume that some kind of radically new technology is made possible by a scientific breakthrough at some time in the relatively near future, what is the significance for MoD? The new technology could find any of a number of defence applications, depending on the military requirements of the time. This is illustrated schematically in figure 1, for some of the potential breakthroughs discussed earlier (as stated before, no assessment is made or implied of the likelihood of these breakthroughs occurring; they are merely used here as an illustrative example).

6 ANTICIPATING THE FUTURE

Standard methods for forecasting future developments in technology are based on extrapolation of current trends. Such methods fail to predict the kind of disruptive technology that might arise from future breakthroughs in fundamental science. This paper has examined historical examples of new technology arising out of revolutionary changes in scientific understanding, and has reviewed the process by which such revolutions occur. It is likely that further scientific revolutions can be expected, though by definition it is impossible to predict them in any detail. However, the paper has been able to summarize the broad factors involved in turning such breakthroughs into practical technology, and given examples of the kind of impact this might have on defence applications.

It is important that any defence planning that looks more than 15 to 20 years ahead should take account of the potential disruption caused by radically new technologies that might alter the fundamental assumptions being made. One approach might be the use of a grid of planning scenarios chosen to encompass all possible future situations, as has been used to good effect both in the military [27] and business [28] worlds.

In the same way that government and private organizations routinely maintain 'technology watch' activities, it is essential to maintain a broad awareness of current research in fundamental science, particularly in areas where rapid or unexpected progress is being made.

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