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Growing scientific citizens in a high-tech world

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Introduction

A few years ago, a number of Edinburgh University academics and their associates produced an admirable source book for citizenship education, *Renewing democracy in Scotland*.[1] The list of contributors was impressively broad, ranging across seven of the University's (then) eight faculties, with the exception of the Faculty of Science and Engineering. This absence is odd. In today's world, science and technology daily present us with conundrums and choices, so that an educated citizen must know how to make informed judgements about these.

Indeed, while none of the contributors to *Renewing democracy in Scotland* was from the Faculty of Science and Engineering, the importance of technology for citizenship education was explicitly acknowledged by Tom Conlon (from the Faculty of Education): '[It] is clear that technology impinges upon major areas of policy including health, ecology and equality. Increasingly, technology issues are coming to the fore of political debate.' Colon defined technology as 'the application of science to change some aspect of the environment'. This model of the relationship between science and technology is very commonly held, but presents a one-sided picture. A more nuanced understanding of the differing nature of science and technology and how they relate to each other is vital to growing scientific citizens in today's high-tech world.

Technology is doing and science is understanding

'Technology' (Greek *techne* = 'art' or 'skill'[2]) is about getting things done, and includes not only the traditional engineering disciplines (building bridges, aeroplanes, computers, etc.), but also medicine and agriculture. Its goal is power: 'Look, I can do that!' 'Science' (Latin *scientia* = 'knowledge') is about understanding how things work. Its goal is insight: 'Aha, I see!' Today, science and technology are symbiotic, but such intimacy is historically recent, and requires explanation. Technology is as ancient as humanity, while science as we know it is not much more than four hundred years old.

The ancient origin of technology is attested across the globe by traditional stories that reach back to time immemorial. Chinese mythology features demi-gods such as *Shénnóng*, literally, 'divine farmer', and *Shuìrèn*, literally, 'stove man'. Interestingly, *Shénnóng* embodies the fantasy of risk-free technology. While tasting plants for edibility and medicinal properties he poisoned himself multiple times, but survived because he was semi-divine! *Shuìrèn* plays the role of Prometheus in Greek mythology, introducing fire

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[1] Eds., Jim Crowther, Ian Martin and Mae Shaw, National Institute of Adult Continuing Education (England and Wales) (Leicester:2003). Here and below, references are selected for their value as further reading.

[2] For a philological history, see Carl Mitcham, *Thinking through Technology: The Path between Engineering and Philosophy*, University of Chicago Press (Chicago & London:1994), Chapter 5.

to humans. In the Hebrew bible we read of Cain’s descendants Jabal and Tubal-cain originating animal husbandry and metal working respectively (Genesis 4:20-22).

These ancient stories witness that in most of history, technology has *not* been ‘the application of science to change some aspect of the environment’: there simply was no science to apply! In contrast, modern science has made use of the latest technology from its inception. Galileo’s telescope depended on new lens-grinding know-how. Demobilised scientists from the Second World War built the first radio telescopes using surplus radar equipment. Today’s particle physicists rely on complex accelerators and detectors. Some scholars suggest that such a ‘technological bias’ determines the very nature of modern science. Thus, the philosopher Amos Funkenstein contrasts a *contemplative* medieval natural philosophy, whose goal was edification, with an *ergetic* (Greek *ergos* = work) modern science: a *knowing by doing* that equates understanding with the ability to reconstruct.[3]

Consider two contemporary sciences in this light. Inside particle accelerators, physicists can recreate the conditions of the first few seconds of the Big Bang, yielding an ‘ergetic’ understanding of nothing less than the universe itself. The implicit goal of biology at least since the discovery of the DNA double helix is the recreation of life from inorganic materials. The rise of the new discipline of ‘synthetic biology’, and Craig Venter’s recent headline-grabbing synthesis of the smallest possible single-cell organism supposedly ‘from scratch’ merely bring this hitherto largely unspoken ‘ergetic’ goal of biology into the open: if we can recreate life, then we can truly claim to understand it.

I find Funkenstein convincing. If he is right, then modern science was ‘born in bed with technology’. In turn, as the philosopher Carl Mitcham has suggested, ‘it is precisely the inherently technological character of science that makes technology in the modern sense possible.’[4] But the birth of modern technology needed one more ingredient: the professionalisation of science. Friederich Wilhelm von Humboldt founded the first modern research university in Berlin in 1810. Henceforth, professional ‘scientists’, a word coined by William Whewell (Master of Trinity College, Cambridge) in 1834, are paid to work in laboratories to enquire systematically into the workings of the world (science), which vastly increases our ability to get things done (technology). The symbiosis between electronics and solid-state physics is a paradigmatic example. Because we understand electrical conduction in semiconductors very well, synthetic materials can be designed for particular applications (e.g. multi-colour light emitting diodes). So, while humans have always lived with technology, the latter’s symbiosis with science has brought about modern *high* technology, characterised by complexity, global reach and rapid change. In such a world, many scientists work as technologists.

Technology involves inevitable risks

The close alliance between modern science and technology may spawn an illusion: that science can deliver risk-free technology. We have already met this fantasy in *Shénnóng*. Today we have exchanged a demi-god for a white-coated scientist. In either case, we want power without risk. This fantasy is illustrated by an interview I heard on BBC Radio 4 at the height of the controversy concerning a possible link between triple mumps, measles

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[3] Amos Funkenstein, *Theology and the Scientific Imagination from the middle ages to the seventeenth century*, Princeton University Press (New Jersey:1986), Chapter V.

[4] Carl Mitcham, *Thinking through Technology*, p. 208.

and rubella vaccination (a new medical technology) and autism. The interviewer asked a scientist whether he could guarantee that the triple vaccine was ‘absolutely safe’, i.e. ‘as safe as aspirin’. For this interviewer, science should be the guarantor of risk-free technology. But this is not possible, because (a) power and understanding are asymmetrically related, and (b) complex systems are chaotic and non-linear.

Consider first the asymmetric relation between power and understanding. While in ‘ergetic’ science there is no understanding without (re)construction, the converse is untrue. Even in an era of rapid scientific progress, construction (technology) is entirely possible, and indeed likely, without complete understanding (science). Consider Dolly the Sheep (5/7/96-14/2/03). Almost none of the steps in the cloning process are understood even today. For instance, it’s unclear why a pulse of electricity could fuse two cells; but it *does* work, sometimes. The accumulated ignorance over some 100 procedures is reflected in the low overall success rate, and in unanticipated effects such as premature aging. Dolly the Sheep is a technological, rather than scientific, breakthrough. A lot of scientific knowledge certainly went into Dolly, and most of the people involved were trained as scientists. But the project was a technological one aimed at making cloning work and (ultimately) using it for other technological ends (such as organ transplantation).[5]

Dolly illustrates how a single technological advance can create multiple puzzles (and indeed, opportunities) for scientists. On the other hand, every advance in ‘ergetic’ science is technological (a successful re*construction* of something or other), which in turn may yield further technological opportunities. In this scenario of technology spawning science which spawns technology, there simply isn’t any hope of understanding (science) ever keeping up with doing (technology), so that the latter will inevitably be risky.

Another risk generator is complexity. A complex system is made up of many interacting components. The planets in the solar system and the sun all gravitationally tugging each other, a bucket of water with over a trillion trillion molecules bouncing off and attracting each other, the cells in a human body communicating via nerve impulses and hormones, the millions of computers in the worldwide web exchanging information, and the stock brokers on a trading floor second-guessing each other’s minds are examples. Complex systems have two features that render them risky to manipulate: chaos and non-linearity.

First, complex systems may show chaotic behaviour, i.e., very small uncertainties in the input parameters used to model them can give rise to dramatic uncertainties in the predicted outcomes. A butterfly flapping its wings in Brazil may turn balmy sunshine into squally showers in London. Secondly, the response of complex systems to perturbations can be highly non-linear. Heat up some water at room temperature by 0.1°C, and its volume will increase a little (a few thousandth of a percent). Such ‘sensible’ response continues until 99.9 °C; then you get a shock – the volume increases by more than a thousand-fold in response to the next 0.1°C rise – the water boils and becomes steam. Stock market crashes in response to changing economic conditions[6] and the possible abrupt cessation of the Gulf Stream in response to global warming are other examples of non-linearity in complex systems. In such systems, the last straw can indeed break the camel’s back – and we do not always know where such ‘critical points’ are lurking.

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[5] For the ethical issues, see *Engineering Genesis: The Ethics of Genetic Engineering in Non-Human Species*, eds., Donald Bruce and Ann Bruce, Earthscan (London:1999).

[6] For a superb introduction to social complexity, see Philip Ball, *Critical Mass: how one thing leads to another*, Arrow Books (London:2004).

Educating citizens about risk

To summarise, the asymmetric relation between technology and science together with the nature of complex systems mean that *technology is inevitably risky*. Grasping this point is essential in a society that is increasingly risk adverse. This is illustrated by a comment from the outgoing chairman of a major pharmaceutical company interviewed on BBC Radio 4, who opined that had aspirin been invented today, it would never have been licensed. This common pain killer probably has more known side effects than any other drug licensed today. Most of these were discovered through continual use since 1899 rather than predicted by pharmacological science. Interestingly, many ‘side effects’ can be harnessed for non-analgesic clinical purposes (e.g. thinning blood after heart attacks). So aspirin, while not ‘absolutely safe’, is indeed one of the safest drugs, *not* because it has no side effects, but because many of its side effects are known and some are even understood. Importantly, such safety for us today comes from previous generations taking risks on our behalf.

Take another example, the bicycle, a form of ‘green’ transport that we are increasingly encouraged to (re)turn to. Perhaps surprisingly, physicists are still not agreed why the complex mechanical system of bicycle-plus-rider should stay upright. Moreover, in road trials, a fraction of riders would undoubtedly fall off, and other safety concerns abound, e.g. risks from cars. I doubt that ‘low-carbon bi-pedal transporters’ would ever be licensed for general public use today! As it is, many generations of users have demonstrated convincingly that humans-on-bicycles can be stable, and have trained us to take on the other associated risks.

These two ‘thought experiments’ show that for society to continue to benefit from technological advances, each generation must take risks for subsequent generations. We urgently need informed public debate and democratic consensus on the degree of such risks that we want to take on as a society, and how we deal with the consequences. To achieve this, citizens need an appreciation of the scale of risks already involved in everyday activities that we all do with little thought, and an understanding of ‘the rules of chance’.

Concerning everyday risks, Richard Wilson has helpfully tabulated activities that would increase the chance of death by 1 in a million in the year 1979 (i.e. if 1 million people all engaged in the activity, one extra death would result), e.g. cycling 10 miles (from traffic accident), flying 1000 miles (from accidents) or 6000 miles (cancer from exposure to cosmic radiation), and drinking two-thirds of a bottle of wine (from liver cirrhosis).[7] Weighing everyday risks helps to put any new technological risks into perspective.

To see the importance of understanding ‘the rules of chance’, consider ‘cancer clusters’, putative cancer ‘hot spots’ associated with some local technology (e.g. a mobile phone base station mast). The epidemiological issues are complex and each case has unique features. But one question is vital in all cases: if cancer strikes at random, what is the likelihood of the observed cluster showing up purely by chance?

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[7] *Technology review* vol. 81, no. 1, pp. 41-6, ‘Analyzing the daily risks of life’; reproduced in reference 13 below.

Answering this question is non-trivial; e.g. one has to consider age variations across different regions. But a simpler example illustrates the essential point. Eye witnesses to German V2 rocket attacks on London in the Second World War repeatedly claimed that the bombs were targeted at particular areas. To test this hypothesis, a scientist[8] divided a 144 km^2 area of south London where 537 rockets landed into 576 squares of ¼ km^2 each, and counted the hits in each square. Since there is an average of 0.932 hits per square, ‘common sense’ may expect that a non-targeted, ‘random’ shower of bombs should lead to most squares (say, about 90%) taking a single hit, with a few (say, about 10%) taking no hits. The real situation is shown below, together with the expected distribution of bombs calculated assuming that they fall randomly.

No. of bombs per square	Actual no. of squares	Expected no. of squares
0	229	226.74
1	211	211.39
2	93	98.54
3	35	30.62
4	7	7.14
5 and over	1	1.57
	576	576.00

The measured distribution bears no resemblance to ‘common sense’, but follows the ‘random-hit’ model, which predicts that, strikingly, nearly 40% of the squares take *no* hits, while nearly 7% take three hits or more. One can see why residents reasoning from ‘common sense’ might have thought that the Germans were aiming at particular targets, especially when those in high-hit neighbourhoods compared notes with those (the majority!) whose neighbourhoods sustained no hit. But post-war investigations show that they were wrong.

The moral is that a completely random process can naturally give rise to ‘clusters’. More generally, this example shows that ‘common sense’ can easily lead us astray when it comes to assessing chance and risk. Thus, when epidemiologists repeat this kind of analysis for cancer clusters, they often find that there is no evidence to bear out ‘cancer hot spot’ theories, i.e. the observed clusters are entirely compatible with chance. Nevertheless, the public seldom believe them.[9] No doubt, this is partly due to the well-entrenched ‘common sense’ approach to chance already noted. But it may also reveal a misunderstanding of what science is, and what and how fast it can deliver.

The scientific process takes time

The word *science* refers to a loose collection of methodologies and processes for generating reliable knowledge about the material world,[10] and to the body of knowledge so generated. Science education has traditionally focussed on the latter. For citizenship education, the former is far more important. I say ‘a loose collection’, because different sciences use methods appropriate to their subject matter. Studying historical processes such as biological evolution or galaxy formation, where laboratory experiments are seldom possible, requires reasoning distinctive from semiconductor physics, where

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[8] R. D. Clarke, *Journal of the Institute of Actuaries*, Vol. 72, p. 481 (1946).

[9] For an illuminating case study involving a communications mast, see A. T. Gavin and D. Catney, *Ulster Medical Journal*, vol. 75, no. 3, pp. 195-199 (2006), ‘Addressing a community’s cancer cluster concerns’.

[10] See John Ziman, *Reliable Knowledge: an exploration of the grounds for belief in science*, Cambridge University Press (Cambridge:1978).

laboratory experiments are routine. ‘Big science’ (astronomy, particle physics), relying on large teams and giant facilities, functions quite differently from ‘small’ laboratory-based sciences.

In ‘small science’, a team typically consisting of an established researcher, a couple of postdoctoral research assistants and a number of PhD students tackles a problem, seeking results within the period of a competitively-awarded grant, typically three years. When results emerge, they will write it up and submit the manuscript to a scientific journal. After weeks to months, the authors receive comments from anonymous ‘referees’– fellow scientists whom the journal editor has asked to evaluate the work. The refereeing process is quite conservative: breakthroughs are often repeatedly rejected. If the authors can persuade the referees, the paper will eventually be published. After the paper is noticed, read and digested, which can take months to years, others will start using its results to build their own projects. The typical ‘lead time’ in applying for and getting new grants is a year or more. The cycle then repeats. Irreproducible data are eventually forgotten, over-hasty theories are replaced by more solid models, and our understanding of a particular problem is gradually refined.[11]

This process *does* generate reliable knowledge (see Ziman’s book of that title), *but it takes time*. As a rule of thumb, consensus is reached over a decade or longer, and the road to this point is tortuous, necessarily littered with false leads, flawed experiments, incomplete data, etc. (It took 4 years to identify the AIDS virus, and 5 more to understand it enough for the first effective ‘combination therapy’ to emerge.) In the process, scientists will argue and disagree with one another repeatedly. Sometimes, after lengthy investigation, the community may even decide that consensus is not yet possible, and collectively ‘ditch’ the subject for the time being.

The ‘natural scientific cycle’ appears slow for the non-specialist. I remember a senior scientist in charge of one of the UK’s main science funding councils being interviewed on BBC Radio 4 concerning a case of scientific fraud by a Korean stem-cell researcher. The interviewer wanted to know why ‘it took so long’ for the fraud to be discovered. The scientist pointed out that the timescale concerned, seven months, was actually amazingly short in terms of the ‘natural scientific cycle’!

Thus, when society gives a problem to science (e.g. ‘Can BSE jump the species barrier?’), it is completely unrealistic to expect science to come up with anything approaching a consensus answer on the time scale of months or even a few years, however much public money is poured in. Unfortunately, many appear to expect precisely such quick results, and end up repeatedly disappointed. They then conclude that science does not have a useful contribution to make. But that would be throwing the proverbial baby out with the bathwater. The right thing to do is to learn collectively how to use uncertain science-in-the-making in the public arena.

Space precludes discussion of this important subject, but an excellent recent volume is available.[12] Instead, I note that it is important not to let current scientific uncertainty cloud

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[11] See John Ziman, *Prometheus bound: science in a dynamic steady state*, Cambridge University Press (Cambridge:1994), for a detailed introduction.

[12] Henry N. Pollack, *Uncertain science, uncertain world*, Cambridge University Press (Cambridge:2003) offers a readable account, with many examples taken from the climate change debate.

our perception of what science *can* confidently offer. For instance, scientists understand the relevant systems well enough to say quite certainly that:

- Rampant use of antibiotics *will* give rise to rapid acquisition of drug resistance amongst microbes (although the detailed mechanisms are still far from fully understood);
- As the globe continues to warm, at some point ocean currents *will* change abruptly giving rise to dramatic climatic consequences (although there is somewhat less consensus on precisely when that point will come and what the consequences may be, but progress is rapid in this area).

These two items illustrate well that it is often not the lack of knowledge that impedes reasoned public decision making!

Conclusion: technology, science and society

There is no doubt that thinking about science and technology is a key part of citizenship education. The modern symbiosis between these two areas of human endeavour has brought tremendous benefits: the life expectancy in the UK has nearly doubled (from 40 to nearly 80) since Whewell coined the word ‘scientist’; over the same period, the price of wheat has dropped by a factor of ten.[13] Technological advances, often enabled by science, have also brought problems, local and global, ethical and political. Citizens should be involved in making decisions about how to continue to reap the benefits responsibly while minimising, or even eliminating, the harms. Science has also brought significant cultural gains. That we now wash hands rather than sacrifice children to avert infectious epidemics is partly due to the growth of the scientific worldview. Society needs to learn how to foster the conditions under which science can continue to thrive. It is salutary to note that the immediate previous president of the Royal Society, Lord May, chose to use his final annual presidential address (2005) to warn of the threat posed by religious fundamentalism to science. I should simply add that science in fact withers under extremisms of all kinds: a militant *scientism* that insists on scientific rationality being the only rationality is just as bad,[14] because all ‘-isms’ (the Hebrew prophets would have called them ‘idols’) will end in disillusionment.

In this short chapter, I have not been able to touch on these fascinating and important issues. Instead, I have concentrated on delineating the different natures of science and technology and their relationship in the modern world, and on discussing why technology necessarily entails risks. An appreciation of these basic issues provides a firm foundation for critical reflection on ethical, political and other questions raised by science and technology. The recently-launched AS level ‘Perspectives on Science’ shows one way in which such material can be integrated into a coherent curriculum. When such integrated teaching and learning becomes widespread, science and technology citizenship education can be considered to have come of age.

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[13] Bjørn Lomborg, *The Skeptical Environmentalist: Measuring the Real State of the World*, Cambridge University Press (Cambridge:2001), chapters 4 and 5.

[14] Tzvetan Todorov, *hope and Memory*, Atlantis Books (London:2005) relates scientism to political totalitarianism.