Between promise, fear and disillusion: two decades of public engagement around nanotechnology

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***Abstract*—Nanotechnology emerged as a subject of public interest and concern towards the end of the 1990's. A couple of decades on, it's worth looking back at the way the public discussion of the subject has evolved. On the one hand we had the transformational visions associated with the transhumanist movement, together with some extravagant promises of new industries and medical breakthroughs. The flipside of these were worries about profound societal changes for the worse, and, less dramatically, about the potential for environmental and health impacts from the release of nanoparticles. Since then we've seen some real achievements in the field, both scientific and technological, but also a growing sense of disillusion with technological progress, associated with slowing economic growth in the developed world. What should we learn from this experience? What's the right balance between emphasising the potential of emerging technologies and cautioning against over-optimistic claims?**

Keywords—nanotechnology, public engagement, education, science policy, productivity

I. Introduction

"Not to lie about the future is impossible and one can lie about it at will"

Naum Gabo & Anton Pevsner, The Realistic Manifesto[1].

Science communicators and educators face a dilemma when talking to the public about an emerging technology like nanotechnology. To talk about the possibilities of nanotechnology necessarily involves making predictions about the future. When we talk about established science, we are dealing with relative certainties. But in talking about technology futures, we must necessarily engage with peoples' hopes and fears for the future, and reflect on how our own views colour what we say. Discussions about our technological future readily turn to those extremes that attract most attention – to utopian or dystopian visions, even if these don't reflect the realities of more sober assessments.

Predictions are difficult to contest, since at any given moment the future is literally unknowable. There's an old joke, which sadly is still current, that says *"fusion power is twenty years in the future, and always will be"*. This reminds us that the future we predict does eventually arrive. There will be those who remember what we said and can judge us on how accurately our predictions turned out. Those judgements will influence how those communicators and educators who come after us will be received.

Nanotechnology is now at the stage where we can make comparisons between what was said a couple of decades ago and what actually transpired. The aim of this article, intended for educators, science communicators, and anyone interested in how we talk about science and technology to a wider public, is to reflect on this experience.

II. The Promise of Nanotechnology

"As we enter the 21st century, nanotechnology will have a major impact on the health, wealth and security of the world's people that will be at least as significant in this century as antibiotics, the integrated circuit, and man- made polymers"

NSF Committee, 1999, Quoted by Ivan Amato in Nanotechnology: shaping the world atom by atom [1].

Nanotechnology, as a division of academic and industrial science and technology, grew in public prominence in the late 1990's; the launch of the USA's National Nanotechnology Initiative in 2001 gave the subject the endorsement of the President of the United States and the (subsequently realised) hope of substantial new funding. The opening quotation – quoted in an official manifesto for the initiative [1] – sums up the promise that its supporters held out for the technology at that time – it was to be the transformational technology of the new millennium.

Underneath this promise was quite a complex mixture of messages and motivations. Nanotechnology was – is – composed of many academic disciplines, both established and emerging, many already in existence well before the invention of the name. The identity of the subject has always been contested between these different disciplines. Nonetheless, some strong themes successfully entered the public consciousness.

The famous image of the IBM logo picked out in individual atoms, made by Don Eigler [2], symbolised a new ability to manipulate matter on an atom-by-atom basis, and this coincided with a rediscovery of Richard Feynman's 1960 lecture "Plenty of Room at the Bottom", appropriated to give the discipline a suitably distinguished historical pedigree [3].

More controversial was the relationship of the new discipline to the ideas developed by the futurist K. Eric Drexler, whose expansive vision of nanotechnology as a

[1] I'm indebted to Patrick McCray for this quotation.

truly world-changing development with the potential to abolish material scarcity and end disease attracted wide attention [4,5]. In particular, Drexler's vision of nanotechnology became a central pillar of the thinking of transhumanists and singularitarians. Transhumanists believe that it will soon be possible to use new technologies like nanotechnology to radically transform humanity; many transhumanists look forward to the "Technological Singularity", a moment at which technological change accelerates in a runaway fashion to create inconceivable changes in the human condition. These notions, and the centrality of Drexler's vision of nanotechnology to them, have received high profile endorsement from prominent figures such as Ray Kurzweil [6].

By the early 2000's, Drexler's vision had become largely marginalised within the scientific community, but it retained (and to some extent still does) enormous and enduring public appeal, entering popular culture through science fiction novels, films and comic books. As I will discuss below, the wide influence of these futuristic ideas offers challenges to educators and those concerned with public understanding of the subject.

If Drexler and the transhumanists saw nanotechnology as the vehicle for the complete transformation of humanity, another widely heard perspective was that of those who believed that nanotechnology offered huge new business opportunities. Talk of "trillion dollar markets" was commonplace, and the perception was of nanotechnology as the next lucrative opportunity for venture capital, following the dot-com and biotech bubbles [7].

This blending of science excitement and business enthusiasm, with Drexler's science fiction vision lurking in the background, was a heady mix. It was inevitable that some would see dangers in such a potentially powerful technology, and it was the anticipation of a widespread public backlash based on these fears that steered much of the public discussion of nanotechnology from the mid-2000's on.

III. In anticipation of a backlash

It was the Drexlerian vision of runaway nanobots that was the initial spark that provoked the fear of nanotechnology. Drexler's vision always was – and remains – more popular in Silicon Valley than amongst practising nanoscientists, so it's perhaps not surprising that it was from those circles that the warning came. The distinguished software engineer Bill Joy's article in Wired magazine [8] worried that the impact of autonomous nanorobots would render humans redundant, at best, or extinct, at worst.

A small NGO previously devoted to campaigning against genetic modification – the ETC Group (Action Group on Erosion, Technology and Concentration) capitalised on this mood with great effectiveness. ETC's report – The Big Down [9] – combined existential worries about runaway nanobots with a much more concrete emerging concern that engineered nanoparticles might have deleterious effects on human health and the environment. With the unlikely help of the UK's heir to the throne, Prince Charles, these concerns gained widespread public exposure.

The response from the international scientific community was motivated by the perception that a public backlash – analogous to the reaction of the public in Europe against genetic modification of food – might derail a promising and potentially lucrative technology.

In the USA, the first National Research Council review of the National Nanotechnology Initiative, in 2002, recommended a programme of research into the "Social and ethical implications of nanotechnology", following the recommendations of an earlier NSF workshop. In the UK, the government commissioned a distinguished panel, under the auspices of the Royal Society and the Royal Academy of Engineering, which recommended a programme of public engagement, saying "a constructive and proactive debate about the future of nanotechnologies should be undertaken now – at a stage when it can inform key decisions about their development and before deeply entrenched or polarised positions appear".

This advice was taken, with a number of organisations, including NGOs, Universities and government agencies, organising quite elaborate forms of public engagement, both concerning nanotechnology in general and specific aspects of the technology (particularly those aspects where there was a particular fear of public controversy, such as potential uses in food).

It's possible to draw some general lessons from these exercises (for a summary, see [10]). Potential applications of nanotechnology with obvious benefits – such as in renewable energy and medicine – were welcomed, and the more general value of new technologies in promoting jobs and economic growth was recognised. But, on the negative side, the questions that were being raised by NGOs like ETC, Greenpeace and Friends of the Earth about potential environmental and toxicity issues did cause disquiet. There were more general anxieties about new technology, too, perhaps less specific to nanotechnology – questions about who controls and regulates new technology.

One of the most important lessons concerns the relationship between risk and trust. The regulation of new technologies is focused on controlling risk, and when scientists and technologists talk about new technologies it is often to risk that the conversation turns, if only because risk is susceptible to experiment and to quantification. But the more relevant – and more difficult – question concerns the degree to which people trust the bodies and institutions introducing and controlling new technologies. It's easy to state the principles that allow one to build trustworthy institutions – transparency and openness, for example. But these may not always be easy to put into practise.

IV. Has nanotechnology lived up to its promise?

The answer to this question, of course, depends on whose promises one believed. The singularity hasn't yet arrived, despite the conviction in 2003 of some proponents of the Drexler vision that the most likely date for the arrival of "exponential general purpose molecular manufacturing" was between 2015 and 2020 [11]. Nor am I yet convinced that we can argue that nanotechnology has had the impact of antibiotics, the integrated circuit, and man-made polymers. Nonetheless, the real contributions are substantial.

In electronics, we've seen a roughly 30-fold increase in processor power since 2000 [12], and there's no question that current integrated circuits represent a working nanotechnology with massive social and economic impact (even though, interestingly, this industry has been reluctant to use the "nano" label). As has long been predicted, the period of exponential growth in computer power has now come to an end, and the promise of nanotechnology to deliver a new phase of growth, based on a new, beyond-CMOS technology, has not yet come to pass.

Molecular electronics did not deliver on its promise of large-scale integrated circuits whose elements were composed of individual molecules [13] – though organic optoelectronic devices, for example OLEDs – have been fully commercialised in mobile phones and television screens. The huge improvements in battery technology that have allowed the electric vehicle sector to grow so fast owe their origins to the control of nanostructure. Semiconductor nanotechnology has led to significant advances in optoelectronics, such as solid-state lighting. Looking to the future, we now see real signs that nanotechnology might provide a scalable substrate for quantum computing, through collective excitations - Majorana zero modes - in semiconductor nanowires in contact with superconductors [14].

Some of the highest hopes for nanotechnology were in the field of medicine. For example, the 2004 Cancer Nanotechnology Plan [15] from the US Government's National Cancer Institute, raised hopes for nanotechnology thus: "*To help meet the Challenge Goal of eliminating suffering and death from cancer by 2015, the National Cancer Institute (NCI) is engaged in a concerted effort to harness the power of nanotechnology to radically change the way we diagnose, treat, and prevent cancer*".

While a "*challenge goal*" is arguably not the same as a prediction or a promise, the gulf between the 2004 vision and the current reality is all too obvious. The US age-adjusted cancer death rate in 2004 was 187 per 100,000, from which value it fell by 15% to 159 per 100,000 [16]. There is no evidence that nanotechnology made any significant contribution to this small improvement.

In fact, the progress of nanotechnology-based anti-cancer therapeutics into the clinic has been considerably slower than first anticipated. In part, this may reflect an intrinsically slower rate of progress in technologies related to biology compared to, say, electronics. Nonetheless, the area of nanomedicine remains very active, with many promising new areas under research [17]. Here again the impact of the reality of steady technological progress is undermined by overstatements and hype.

So should we be disappointed by the progress of nanotechnology in the last couple of decades? This depends on what our expectations were. If we had believed the hype, disappointment would be justified, but perhaps if there had been more realism in in setting those expectations in the first place, then the actual progress would have been more obvious and more impressive.

V. Accelerating change or innovation stagnation?

There's a paradox in the wider landscape for the discussion of new technologies at the moment. On the one hand, everyone is familiar with new consumer technologies that are rapidly introduced and soon taken for granted. For science communicators and educators, the natural tendency is to emphasise the novel, and there's a widespread consensus that technological progress is accelerating ever faster.

And yet, the economic facts on the ground don't support this position. The expectation is that technological progress should result in continual increases in productivity – we should be able to produce more economic value from the same inputs. What we've seen instead – particularly since the global financial crisis (though there is some evidence the problem predates this) – is a slowdown of the rate of productivity growth across the developed world [18].

Productivity may seem like an abstruse and abstract economic concept, but the consequences of a slowdown in productivity growth are immediate – this is a major driver of the phenomenon of stagnating wages, and the sense that living standards can now longer be relied upon to rise from generation to generation.

There is no consensus about cause of this productivity slowdown. Some attribute it simply to a mis-measurement issue – that economic aggregates such as gross domestic product do not completely capture the benefits of new technology. There are arguments that the efficiency of the R&D process itself is declining [19]. The most fundamental suggestion, made by some very prominent US economists, is simply that we have already harvested the "low-hanging fruit" of technology [20], and that new technologies that have emerged over in recent decades, and which are emerging today, simply do not have the same potential to transform the economy as earlier technologies, such as electrification, the automobile, and the telephone [21].

These arguments are not very appealing to practitioners and communicators of science and technology, but they need to be taken seriously. One alternative view is that today's new technologies still have the potential to be transformative, but that changes in the wider innovation system have slowed down the process of transferring new technologies from the laboratory to new and improved processes and products.

For the science communicator, perhaps one key message should be the need to appreciate that some audiences may be less receptive to the idea of continuing technological progress, if their lived experience is of increasing insecurity and stagnating living standards.

VI. Conclusions and reflections

After two decades of science communication and public engagement around public engagement, perhaps we're in a position to learn some general lessons. We should bear these in mind, not only in future education and outreach for nanotechnology, but for other emerging technologies. Otherwise, there's a danger that in new areas – synthetic biology, quantum technology, computational neuroscience, artificial intelligence – the same mistakes will be made.

What these emerging technologies have in common is that they operate in what has been called an "economy of promises" [22]. Inevitably, funding in the present needs to be justified by claims about the future, and it's all too easy for these claims to become overly extravagant.

These claims may be about the economic impact – "the trillion dollar market" – or on revolutions in fields such as sustainable energy and medicine. It's essential to be able to make some argument about why research needs to be funded and it's healthy that we make the effort to anticipate the impact of what we do, but there's an unhealthy, if possibly inevitable, tendency for those claimed benefits to inflate to bubble proportions. Scientists feel that these claims are necessary in grant applications and papers, while the media demand big and unqualified claims to attract their attention. Even the process of considering the societal and ethical aspects of research, and of doing public engagement, can have the effect of giving credence to the most speculative possible outcomes [23].

In a field like nanotechnology, relatively incremental developments of existing technology coexist with much more radical possibilities, and this leads to a tension: the promise is sold on the grand vision and the big metaphors, but the achievements are largely based on the aspects of the technology with the most continuity with the past.

The trouble with all bubbles, of course, is that reality catches up on unfulfilled promises (for a recent cautionary tale, see [24] on the medical diagnostics company Theranos), and in this environment people are less forgiving of the reality of the hard constraints faced by any technology. If one overdoes the promise, disillusionment sets in amongst funders, governments, investors and the public. This might discredit even the genuine achievements the technology will make possible. Maybe our constant focus on revolutionary innovation blinds us to the real achievements of incremental innovation – a better drug, a more efficient process for processing a biofuel, a new method of pest control, for example.

For the case of nanotechnology, there has been the specific issue of how one should engage with the speculative vision of nanotechnology associated with K. Eric Drexler. For those who do not accept the feasibility of such visions in reasonable timescales, and wish to reflect the scientific consensus, there have been three approaches.

The first approach has been simply to ignore it. In some popular books and articles about nanotechnology, Drexler is simply written out of the history of the subject. I think this is not satisfactory – the public is extensively exposed to these ideas, and will be confused by their omission. The second approach is to dismiss them by an appeal to scientific authority. The comments of the late Richard Smalley [25] have often been used in this way. In a world where the authority of experts is questioned more than ever, this seems to me to be an unwise approach to science communication.

My own approach, in my 2004 book Soft Machines [26], in many public lectures, blogposts and articles (see especially [27]), has been to engage with the arguments, in technical detail where necessary, and (I hope) with due respect to their proponents, even when I think their arguments are misguided. This seems to me to be a truer reflection of the character of science.

The philosopher Alfred Nordmann has called for an ethics of science communication [28]. Even accepting that science communication may sometimes have as its goal, not the disinterested pursuit of truth, but the strategic aim of "*creating a robust environment for social and technical innovation*", there still needs to be a principle of "*responsible representation*", which "*involves determinations of plausibility in light of ongoing trends rather than radical novelty*" and "*requires that communicators take responsibility for their representations by being prepared to defend their credibility*".

It is fair, in retrospect, to say that communicators of nanotechnology have not always held to this high ideal.

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