NOTES AND RECORDS
THE ROYAL SOCIETY JOURNAL OF THE HISTORY OF SCIENCE

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Journal:	*Notes and Records: the Royal Society journal of the history of science*
Manuscript ID	RSNR-2017-0034.R1
Article Type:	Research
Subject:	20th Century science < HISTORY OF SCIENCE, 17th Century science < HISTORY OF SCIENCE
Keywords:	curiosity, history, science, einstein, thatcher

The curious history of curiosity-driven research

by

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Abstract. Curiosity has a curious place in the history of science. In the early modern period, curiosity was doubled-edged: it was both a virtue, the spring for a “love of truth”, but also the source of human error and even personal corruption. In the twentieth century, curiosity had become an apparently uncomplicated motivation. Successful scientists, for example Nobel Prize winners in their lectures and biographies, frequently attributed their first steps into science to a fundamental curiosity, an irrepressible desire to ask the question ‘why?’. The aside made by Albert Einstein in private correspondence in 1952 – “I have no special talents. I am only passionately curious” – has now become a meme. Yet in the twentieth century, science was shaped by many forces, and the practical utility of science in the real, messy problematic worlds of its formation seem far removed from the seeming innocence of curiosity-driven research. In the lecture and this paper, I ask why scientists say they ask ‘why?’, and trace the curious history of the idea of curiosity-driven science. In particular, I distinguish between a long and short history of curiosity in science, with the latter associated with the term “curiosity-driven science” and the UK administration of Margaret Thatcher.

Keywords: curiosity; history; science; Einstein; Thatcher

In this lecture I will be curious about curiosity. I will ask the ‘why?’ about asking ‘why?’. Curiosity has come to play an important, perhaps central, role in the stories we tell about science in public, and how science contributes to the public good. My aim here is threefold: to provide evidence for my claim that the language of curiosity has become widespread in public framings of science, and to trace a long and a short history of its rise to prominence.

I think I first noticed the roles played by curiosity when reading the words of scientists who have won Nobel Prizes. The following statements come from a variety of modes of public communication, from interviews with Nobel winners to the words spoken at Nobel banquet speeches. But there is a common thread: mention, time and time again, of curiosity. For example, when Japanese molecular biologist Yoshinori Ohsumi won the 2016 Nobel Prize in Physiology or Medicine for his work in the field of autophagy, or how cells eat themselves, a close colleague, reported in *Nature*, said: “Ohsumi never overlooks anything even in the most banal kind of experiment … He doesn't care about whether it will lead to something useful, whether a breakthrough can be expected, whether it will lead to more funding. He just follows his curiosity.”[1] Australian-born 1975 chemistry Nobellist John Cornforth attributed his prize to ‘a lifelong curiosity about the shapes, and changes in shape, of entities that we shall never see; and a lifelong conviction that this curiosity will lead us closer to the truth of chemical processes, including the processes of life.'[2] Italian Physicist Carlo Rubbia, leader of the team that found the W and Z particles and who received the Nobel in 1984, spoke of the work of his great European laboratory at CERN in the following terms: 'what is fundamental, it is based on curiosity. All these scientific achievements are driven by curiosity.'[3] These three examples are typical of scientists presenting curiosity as a motivation for current work.

Curiosity, by their own testimony, also led scientists into science. American scientist Phillip Sharp of MIT, Nobel Prize winner for physiology or medicine, 1993, cofounder of Biogen, remembered his entry into science: 'It was a step driven by curiosity. I clearly did not want to spend my life being a farmer. I enjoyed the life when I was young, but it was not very intellectually stimulating, and the world was very confined. … Science gave me the opportunity to continue learning'.[4] German Christiane Nüsslein-Volhard, Nobel Prize winner for physiology or medicine, 1995, on the genetic control of embryonic development, when asked 'what drove you into science?', answered: 'I think a very big curiosity. I am very curious and I like to understand things. And not only science, I try to find out why and how things work. Science and nature caught my eye… '.[5] Indeed, the present Royal Society President, Sir Venki Ramakrishnan (chemistry, 2009) said in his Nobel biography: 'People go into science out of curiosity, not to win an award.'[6]

Within this talk of curiosity, there is another structural theme: curiosity in science is linked, time and time again, to curiosity in children. The British radio astronomer Antony Hewish (physics, 1974, for aperture synthesis and pulsars) said in an interview:

> From the earliest days I was taking things apart (and usually breaking them). I just wanted to know how things worked. The only real way to do that is to get inside them. [The curiosity] was always there, I think. I don't know. It certainly didn't come from my family, because my father was a banker … I was just a curious child. I just wanted to know how things worked.[7]

Or take Maurice Wilkins. He won a share of the Nobel Prize awarded for the elucidation of the structure of DNA. His parents, say the authors of his Royal Society *Biographical Memoir*, 'encouraged technical curiosity and were well enough off to support him quite early on with a garden workshop equipped to support lens grinding for ambitious telescopes and for the construction of quite sophisticated model aeroplanes that could fly'.[8] Likewise American George Smoot (physics 2006, for cosmic microwave background radiation anisotropy) recalled: 'My parents respected education very much … they were both technically orientated … I think in one sense I have never grown up, I kept indulging my curiosity, I keep wanting to know how the universe works'.[9]

There's a significant variant of this emphasis on the curious child. It is that formal education discourages the innate curiosity of the child, and the scientist is the child who survived. For example, Leon Lederman who was director of Fermilab and won the 1988 physics Nobel for his work on neutrinos, said:

> Children are born scientists. They do everything scientists do. They test how strong things are. They measure falling bodies. … they learn the physics of the world around them. They are all perfect scientists … They ask questions, they drive parents crazy with why? Why? Why? Then somehow they go to school and the school system crushes their curiosity, converts them to timidity and fear of science.[10]

Or consider the following observation from the cosmologist Hermann Bondi, who began a review of Freeman Dyson's *Disturbing the Universe* (1979), with an unsolicited and remarkable provocation, that leads to the statement that 'curiosity must indeed be the mainspring of scientific endeavour':

> Occasionally I feel unkind towards my many friends and colleagues in the education industry by pointing out that every small child makes a nuisance of itself by constantly asking "Why?", that society has developed a marvellous defence mechanism called education, and that this is so effective that it stops almost everyone from keeping on with this questioning. The few failures of this cure are, I claim, called scientists.[11]

The source, or indeed apotheosis – I use the word advisedly, as the elevation to divine status - of this theme can be found in the self-fashioning of the preeminent figure of modern science: Albert Einstein. Aged 67, writing for the Library of Living Philosophers at the invitation of the editor Paul Arthur Schilpp, Einstein stated: 'It is a miracle that curiosity survives formal education. It is, in fact, nothing short of a miracle that the modern methods of instruction have not entirely strangled the holy curiosity of inquiry'.[12]

This line – the 'holy curiosity of inquiry' was repeated in Einstein's last interview, with *Life* magazine's William Miller. Sandwiched between adverts for carpet cleaners and, ironically, "Halo" shampoo products, this 'intimate glimpse', titled 'Death of a genius. His fourth dimension, time, overtakes Einstein', has Miller turning up on Einstein's doorstep with Miller's son, Pat, and an intermediary, Professor William Hermanns.[13]

> Einstein looked at Pat and simply asked, "Does not the question of the undulation of light arouse your curiosity?" … "Yes, very much", said the boy, his interest brightening.
>
> "Is not this enough to occupy your whole curiosity for a lifetime?"
>
> "Why, yes," said Pat, smiling rather sheepishly. "I guess it is."
>
> "Then do not stop to think," said Einstein, "about the reasons for what you are doing, about why you are questioning. Curiosity has its own reason for existence. One cannot help but to be in awe when he contemplates the mysteries of eternity, of life, of the marvellous structure of reality. It is enough if one tries merely to comprehend a little of this mystery every day. Never lose a holy curiosity."[14]

These aphorisms are still circulating today, in the radically decontextualized genre of the internet meme (see Figure 1).[15] There is a clearly a contemporary appetite for sharing and recirculating this view of curiosity.

[FIGURE 1 HERE]

But let us pause to be curious about this modern and specific sense of curiosity: its identification with the child – with the suggestion that curiosity is innate, a stable, natural and universal given capacity – and of the scientist as adult as the grown up child who remained curious, despite formal education. Einstein said curiosity had its own reason for existence. Well maybe. But there are other reasons too, and we should stop to think about the reasons for curiosity to take the forms it does in modern societies. Curiosity has not always been the same. Curiosity, crucially, is a historically contingent entity that has historically diverse reasons to exist in subtly different forms at different times and in different places.

'Ambiguity characterises curiosity in all its manifestations throughout the early modern period', says Barbara Benedict, in her cultural history of curiosity in the sixteenth to eighteenth centuries.[16] Early modern curiosity was significantly different from Einstein's or our curiosity, it was the source of truth and error, the sign of a free intellect and the stigma of corruption. Such a notion was warranted by the Bible – we can think of Eve and the apple as an example – for there we find that curiosity was a 'mark of discontent', something that betrayed the desire to know or possess more than one was given by God's providence. Curiosity was sinful: the 'lust of the mind', said Thomas Hobbes, or 'vanity', said Blaise Pascal. (For the lecture, I memefied these two early modern sentiments, ready to share.) Cabinets of curiosity, those private, individual museums of the extraordinary, that flourished in the intellectual culture of early modern Europe, may be to our modern eyes delightful collections of the exotic and the strange, but they were also potentially dangerous. Who, after all, was doing the classifying? What objects were possessed in private? What secrets were being pried into? Were they the expression of the sin of pride?[17]

However, Francis Bacon in *The Advancement of Learning* of 1603 'passionately contradicted the theological prohibition against curiosity as the "originall temptation and sinne"'.[18] And, as Benedict puts it, from the Restoration onward, from 1660 to 1820, 'curiosity rose to a peak of frenzied attention', as, to quote her, 'scientists, journalists, women, critics, collectors, parvenu middle-class consumers and social reformers asked questions that challenged the status quo.'[19]

In his Baconian history of the Royal Society of 1667, Thomas Sprat wrote:

> It is strange that we are not able to inculcate into the minds of many men, the necessity of that distinction of my Lord Bacon's, that there ought to be Experiments of Light, as well as of Fruit. It is their usual word, What solid good will come from thence? …
>
> But they are to know, that in so large and so various an Art as this of Experiments, there are many degrees of usefulness: some may serve for real, and plain benefit, without much delight: some for teaching without apparent profit: some for light now, and for use hereafter; some only for ornament, and *curiosity*.
>
> If they will persist in contemning all Experiments, except those which bring with them immediate gain, and a present harvest: they may as well cavil at the Providence of God, that he has not made all the seasons of the year, to be times of mowing, reaping and vintage.[20]

In other words, some experimental knowledge might be useful now, and these are the experiments of fruit; but some, perhaps apparently ornamental or motivated by curiosity, the experiments of light, may well be useful later. This spectrum of research, as defended by Sprat, which made curiosity as justified a reason as utility, has therefore been part of science's rhetorical armoury for some time.

We can find Sprat's quotation, reproduced in full, in Peter Medawar's *Advice to a Young Scientist*, published in 1979.[21]

(Medawar, of course, is the third name of the Wilkins-Bernal-Medawar Medal and Lecture. He was an immunologist – his work of the rejection of skin grafts in mice led to him receiving the Nobel Prize in 1960, shared with Frank Macfarlane Burnet, whose immunological hypothesis Medawar's experimental results supported. Medawar was also an accomplished and witty public scientist, through books, essays and radio, notably the Reith Lectures in 1959. It is in this public context, of course, that he lends his name to this lecture.[22])

Elsewhere in *Advice to a Young Scientist*, where Medawar is discussing the reasons for going into science, he is strikingly dismissive of curiosity as a sole cause. 'Conventional wisdom has always had it that curiosity is the mainspring of a scientist's work', he wrote, adding this has 'always seemed an inadequate motive to me; curiosity is a nursery word'.[23] Yet the context for Medawar's approving quotation of Thomas Sprat complicates this picture, and I think provides a significant clue to how to think historically about curiosity and curiosity-driven research in particular.

Just prior to quoting Sprat, Medawar was discussing different categories of science. For example, he argued that:

> One of the most damaging forms of snobbism in science is that which draws a class distinction between pure and applied science. It is perhaps at its worst in England, where the genteel have a long history of repugnance to trade or any activity that might promote it. Such a class distinction is particularly offensive because it is based upon a complete misconception of the original meaning of the word pure— the meaning that was thought to confer a loftier status upon pure than upon applied science.[24]

"Pure", he noted, 'was originally used to distinguish a science of which the axioms or first principles were known not through observation or experiment … but through pure intuition, revelation, or a certain quality of self-evidence'. Distinguished by logical structure rather than quality, pure science wasn't meant to be simply better or sounder science. Of course Medawar, equally at home in the hypotheses of immunological theory and the messy practice of tissue grafts and organ rejection, was well placed to insist on the falseness of the opposition between pure and applied science. But snobbery of a form does creep in. The immediate context for quoting Sprat is Medawar's criticisms of the "customer-contractor" principle. This notion, that for science necessary for the work of government departments, the customer (the government department, say the Ministry of Agriculture) should state what it wanted and contractors (research laboratories) should do it, was introduced by Lord Rothschild in 1971 and accepted by Edward Heath's government (in which Margaret Thatcher was the minister for education and science). It is significant in the history of UK science policy for its novel framing of policy by the language of the market – of customers and contractors.[25] As Medawar wrote:

> The most sinister consequence of looking down on applied science was a backlash that has diminished pure science in favor of its practical applications and that culminated in England in the injudicious advocacy that sought to fund research on the basis of the retail trade: the so-called consumer [sic]-contractor principle.[26]

Medawar then cites Sprat, and with it the authority of the Royal Society, in support of the necessity of experiments of light, pure science, and curiosity.

This conjunction is the clue. It makes us think that perhaps the modern history of “curiosity” in general and “curiosity-driven research” in particular lies in the politics of making distinctions between categories of science.

This is where historians can help. Categories such as “pure science”, “applied science” or “curiosity-driven science” are not natural kinds. They are powerful rhetorical tools, forged by people in the past for particular reasons. Historians in recent years have done excellent work scrutinising the histories of such categories. I am thinking of Robert Bud and Graeme Gooday on “applied science”,[27] David Edgerton on “defence research”,[28] David Edgerton and Sally Horrocks on “industrial research”,[29] Sabine Clarke on “fundamental research”,[30] and Benoît Godin on “innovation”.[31]

Each of these histories is fascinating. Like “curiosity”, “innovation” was once deeply ambiguous , and during the Reformation took on an especially negative, common meaning. Innovation was dangerous, upsetting, and unwanted.[32] Only very recently – in the nineteenth or even twentieth centuries - has “innovation” been attached to technologies, or assumed its familiar positive sense. In early modern times a ‘university innovation hub’ would have been quickly burnt to the ground.

But the histories of “pure” and “applied” science are most relevant here. If we take Britain as our case study, we can see that the nineteenth century had witnessed a sustained campaign by what the historian Frank Turner called ‘public scientists’ who were intent on securing a substantial public, ultimately state, endowment for science, alongside improved professional status, resources and respect.[33] In this context a distinctive Victorian and Edwardian social contract for science emerged, one in which the autonomy of “pure science” was promoted in return for eventual, longer-term practical returns. Terms such as “fundamental research” were invented as part of the finessing of this deal. As Sabine Clarke has shown, the term has its primary origins in the policy-making of the Department of Scientific and Industrial Research, the new government body established in 1916; the DSIR promoted “fundamental research” precisely because it harnessed the public scientists’ “pure science” to something “with specific ends in view”, that is to say more practical, problem-solving aims.[34]

I see this contract as making historical sense in the context of a world where problems are constantly being articulated. The incessant pressure to respond to immediate problems – of the clinic, the farmer, the factory, the army and navy – what I call ‘working worlds’ and which formed the organising concept of my survey of twentieth-century science[35], was precisely the force that encouraged the separatist language of purity.

It is here that we find the stirrings of a reawakened notion of curiosity-driven research. It is, in the 1920s and 1930s, a minor synonym of pure science. So, to just take one example, the physiologist W.B. Hardy, director of Cambridge’s Low Temperature Research Station, as well as the Torry Research Station near Aberdeen and the Ditton Laboratory in Kent, all research spaces relating to solving the problems of food preservation and supply, had ‘acquired the reputation for allowing the free pursuit of research impelled by the investigators’ curiosity rather than the need to solve a practical or technical problem’.[36] We can resolve this paradox – why would someone so self-evidently working in practically relevant institutions cultivate a reputation for leading research that seemingly does the opposite - when we note that the insistence on following curiosity is defensive and rhetorical rather than something to be accepted at face value.

One person who proposed to modify radically the social contract, and is the exception that proves the rule, was the x-ray crystallographer and socialist John Desmond Bernal. (Bernal is the second of our trio who lent their names to the Wilkins-Bernal-Medawar Medal and Lecture.[37]) In the 1930s, Bernal argued that science was so functionally important for solving the world's problems that it must be guided by the state. Bernal's map of science can be seen in Figure 2. The scientific disciplines are at the top, the applied sciences are in the middle, and the problems science might solve are at the bottom. So, if we zoom in (Figure 3), we see that biochemistry is the science behind food preservation which in turn will solve problems for cooks.

[FIGURE 2 (ideally rotated and across whole page) followed by FIGURE 3 here]

In *The Social Function of Science* (1939) he took aim at the likes of Thomas Henry Huxley who had defended the ideals of pure science, not least because, as Huxley had written "the history of physical science teaches (and we cannot too carefully take the lesson to heart) that the practical advantages, attainable through its agency, never have been, and never will be, sufficiently attractive to men inspired by the inborn genius of the interpreter of Nature, to give them courage to undergo the toils [necessary to serve science]".[38] Here's Bernal:

> That scientific research is profoundly satisfying to all who choose to undertake it is undeniable. … the growth of the profession of science to its present dimensions is not a sign of a spontaneous increase in the number of individuals with natural curiosity, but of the realization of the value that science can bring to those who finance it. For this purpose the psychologically pre-existing natural curiosity is utilized. Science uses curiosity, it needs curiosity, but curiosity did not make science.[39]

Indeed, 'whatever the scientists themselves may think', concluded Bernal, 'there is no economic system which is willing to pay scientists just to amuse themselves'.[40] The idea that scientists merely satisfy a 'psychological aim', the satisfaction of curiosity, was, for Bernal naïve. Instead, under socialism, science should be planned to solve problems 'in the service of man'.

As an aside, since Bernal cast curiosity-motivated research as a psychological – we might say merely psychological – aim, what did the discipline of psychology have to say about the subject? William James in the 1890s made passing comments on curiosity, notably distinguishing between common curiosity as a 'biological function', a shared instinct we deploy 'in approaching new objects' and the more specific 'scientific curiosity', a form of 'metaphysical wonder' with which 'the practical instinctive root has probably nothing to do' but rather occurs when 'the philosophical brain responds to an inconsistency or a gap in its knowledge'.[41] But curiosity became a major focus of psychological research in the mid-twentieth century. The leader of this research was Daniel Berlyne, who was Salford born (1924) and educated at Manchester Grammar School, before progressing to Cambridge, and then to a PhD at Yale on curiosity as a psychological topic. He was forced to return to Britain for visa issues and spent time writing up his results at the University of Aberdeen (1953-1957), before returning across the Atlantic, spending the remainder of his career in the United States and Canada.[42]

Berlyne published his paper 'A theory of human curiosity', based on the Yale work but whilst living in Aberdeen, in 1954.[43] It was followed in 1966 by the paper 'Curiosity and exploration', the most cited piece of scientific literature on curiosity. Berlyne argued that incongruity, surprisingness and complexity were the three distinguishable and measurable factors that prompted curiosity in animals.[44] (Figure 4 shows his test for curiosity in infants. Berlyne watched to see whether his subject's eyes moved towards the more or less complex shape.) Furthermore, in higher animals he identified a capacity of 'epistemic curiosity', in which the three factors play out in dissonances in knowledge. To investigate curiosity in adults, Berlyne read to his subjects questions about animals. A surprising question – say 'do rabbits have wheels?' – would, he found, incite more curiosity than non-surprising questions. These questions had visual analogues too, as we can see in Figure 5.[45]

[FIGURE 4 and FIGURE 5 here]

But I can't look at rabbit-cars without thinking of duck-rabbits. The famous gestalt image – we switch between seeing a duck and seeing a rabbit – was used by Ludwig Wittgenstein and then, in my field, history of science, by Thomas Kuhn in his *Structure of Scientific Revolutions* of 1962, contemporary with Berlyne's work. Kuhn's model of science, in which in 'normal' periods, scientists are constrained by the assumptions of the paradigm, is one in which curiosity was strictly delimited.[46] It was science as problem solving, but also in a highly constrained way; there is none of the essential openness to the wider problems of the world that we see in Bernal, or, for that matter, my working worlds model.

Let's return to the science policy history of curiosity-driven research. In 1968, the US National Science Foundation published the results of Project TRACES. Stung by Department of Defense claims of a minimal influence, the NSF researchers had turned to history of science to justify the importance of basic science. The method was to examine the chain of research that led to five major innovations, and then see what of this research was mission-oriented and what was not. Figure 6 shows the mapped out chains of research leading to the innovation of the electron microscope. The triangles are mission-oriented – that is to say research directed with an overall aim in mind. The circles are "nonmission research" – undirected, pure, free research, of the kind, of course, supported by the NSF.

[FIGURE 6 and FIGURE 7 here]

We can zoom in. In Figure 7 we can see the dot for Max Planck's development of quantum theory in 1900, a step on the way to the electron microscope. A couple of comments. First, we now know, through David Cahan's history of the Physikalisch-Technische Reichsanstalt (PTR), the German imperial standards laboratory in Berlin, that Planck's quantum theory was developed to make sense of data generated by the PTR in order to solve problems for the German electrical light and power industries.[47] Quantum theory was partly a response to the working world of industry.[48] It has to be framed in certain, deliberate ways to be cast as "nonmission" or pure science.

Second, in Britain directly similar, parallel work to Project TRACES began to deepen the concept of curiosity-driven research. In the late 1960s, the UK government's Council for Scientific Policy launched a major investigation that sought to quantify the economic benefits of scientific research.[49] Two scientific civil servants, the economist Ian Byatt and Adrian Victor Cohen, devised a quantified model that sought to capture the economic benefits of science, and in particular measure and predict 'a major and hitherto unquantified benefit, namely the long-term economic benefit of curiosity oriented research'.[50] Byatt and Cohen tested their model with a case study: quantum mechanics again. A substantial programme of follow up work to apply, explore and critically test the model was commissioned, drawing in Fred Jevons and team at the University of Manchester, Chris Freeman at SPRU in Sussex, and the system modellers at the Atomic Energy Authority; each of these groups produced papers and publications.[51] Thus the emerging academic science policy pioneers were enrolled.

Byatt and Cohen concluded that pure research, including the "curiosity-oriented research" of the study 'tends to give rise to major industries in about one generation'. But there were problems. The Manchester group recoiled, arguing that science-technology relations were 'normally too complex to lend themselves to the Byatt-Cohen method … Only rarely is it possible to pinpoint specific curiosity-oriented discoveries from which wealth-producing applications are derived'.[52] The Atomic Energy Authority modellers also ran into problems, complaining that despite their efforts to crunch the data, to do the work properly would require 'great expertise in history of science'.[53] We might also remember that the subject of Byatt and Cohen's initial test case, quantum mechanics, as Cahan had shoed in his history of the PTR, was not a simple case of curiosity-oriented research.

The point is that this work of the late 1960s and early 1970s, the most substantial attempt to investigate, theoretically and empirically, the contribution of curiosity to science and to its economic impact, work which drew on the resources of the state and the most vigorous academic centres of the day, foundered. The facts of curiosity's contribution remained uncertain, and in the absence of certainty, what can be said?

The 1970s language of "curiosity-oriented research", which came from these studies, was replaced, in the late 1980s, by "curiosity-driven research", as the Google Ngram in Figure 8 makes clear. Note the sharp spike.

[FIGURE 8 here]

The context for this spike has been the focus of my most recent historical research. I am exploring science and science policy under Margaret Thatcher now that we can, for the first time, trace these discussions, arguments and events through primary sources released at the National Archives. Science, the recipient of generous state funds and the potential source of innovation and new industries, was a recurrent policy matter for Thatcher, given her radical programme of the transformation of Britain. It is a topic given extra piquancy by her training and experience as a working scientist. Indeed, within days of entering Number 10 Downing Street in 1979, she had decided to reserve first responsibility for science policy to herself, citing her own expertise. She sought and commented directly on scientific advice. In figure 9, for example, is the list of atmospheric chemistry equations that she requested for inspection in 1984. In figure 10 we can see an extract from one of the papers placed in the Prime Minister's box of working papers. The distinctive pen marks, which are blue in the original, show what Thatcher was reading.

[FIGURE 9 and FIGURE 10 here]

What is becoming clear from my historical study of 1980s' UK science policy is that there was a sharp shift in science policy, one that separated Thatcher's early and late years as Prime Minister. Early on, say 1979 to 1987, there were increasing frustrations with the unresponsiveness of science to markets, and rising anxieties among ministers about maintaining the state of the 'science base' as state funding was cut back. Then there was a crystallisation of policy: government funding for near-market research was abruptly curtailed (because private industry should step up), and, to balance this, the science base, especially "curiosity-driven research" was heralded.

The details of this history are convoluted, but the proximate steps towards the ascendance of "curiosity-driven research" in UK science policy were as follows. In the early 1980s the common division of science into kinds or types had been threefold. As her chief scientific adviser Robin Nicholson had briefed Thatcher in 1984:

> Basic research is that undertaken primarily to acquire new knowledge, without any particular application in view. Strategic research covers the area where basic concepts are established, but where it is not yet possible to identify specific products or processes. Applied research is directed towards a specific practical aim, such as the development of new products or processes.[54]

Curiosity in this first phase of Thatcher's administration was barely mentioned. When it was, indeed, the reference was as likely to be derogatory as otherwise. Here, for example, is Nicholson offering characteristically forthright advice, in this instance on the question of whether the UK should withdraw its subscription to the high energy physics laboratory, CERN:

> Withdrawal from CERN must be contemplated as one option on completion of the study – it would be unreal to exclude it. Personally I doubt that it will come to that. More likely will be recommendations to improve the cost-effectiveness of CERN (you've seen the gold plating yourself) and, crucially, to slow down the pace and hence the rate of spend on this area of research. There is no reason why the tax-payers of Europe and the USA should have to fund a private race between two scientific cliques carried out at a pace determined largely by their own *curiosity* and arrogance.[55]

In December 1987 the eminent Cambridge molecular biologist Max Perutz laid into a government report called 'A Strategy for the Science Base' in an article for *New Scientist* magazine titled 'How to stifle innovation'.[56] The attack received a warm and immediate reception from the science advisers closest to Thatcher, notably John Fairclough (who replaced Nicholson) and in particular George Guise in the later, crucial period, because it suggested a way of legitimating the curtailing of near-market research. Thatcher herself read the Perutz article, as we can tell by the blue ink.[57] It might have particularly provoked her with its mention of monoclonal antibodies – an exemplary case for her of British science's failure to make profits. Thatcher, again, underlined these words in blue. Perutz attacked mission-oriented science. He gave a list of great innovations, stating that they 'all arose from basic, curiosity-motivated research'. George Guise urged Thatcher: this was the right approach to science policy. Even Silicon Valley, Guise wrote, implausibly, was the result of curiosity-driven research.[58] The critical point was that Guise and Thatcher regarded state intervention as deeply undesirable, and this included public funding for near market research. The ideological desire to remove the state's role from funding much applied research was the obverse of the new enthusiasm for "curiosity-driven research". They were two sides of the same science policy coin. "Curiosity", especially since the late 1980s, is not a neutral, childlike character, if it ever was, but a term wielded for political purpose.

Thatcher's new policy was fully expressed in her famous Royal Society speech of 27 September 1988. Her speech, which took place in the Fishmongers' Hall in the City of London rather than at the Society's headquarters, is remembered today primarily for her call to arms on anthropogenic climate change. (That, by the way, was another abrupt turn for Thatcher; there is documentary evidence to suggest she was a leading sceptic in 1979.[59]) But the other important announcement was on curiosity:

> Of course, the nation as a whole must support the discovery of basic scientific knowledge through Government finance. But there are difficult choices and I should like to make just three points.
>
> First, although basic science can have colossal economic rewards, they are totally unpredictable. And therefore the rewards cannot be judged by immediate results. Nevertheless the value of Faraday's work today must be higher than the capitalisation of all the shares on the Stock Exchange!
>
> Indeed it is astonishing how quickly the benefits of curiosity driven research sometimes appear. …
>
> Second, no nation has unlimited funds, and it will have even less if it wastes them. …
>
> So what projects to support? Politicians can't decide and heaven knows it is difficult enough for our own Advisory Body of Scientists to say yea or nay to the many applications. I have always had a great deal of sympathy for Max Perutz's view that we should be ready to support those teams, however small, which can demonstrate the intellectual flair and leadership which is driven by intense curiosity and dedication.[60]

She concluded:

> Mr. President, this country will be judged by its contribution to knowledge and its capacity to turn that knowledge to advantage. It is only when industry and academia recognise and mobilise each other's strengths that the full intellectual energy of Britain will be released.

It is this speech that gives us the modern prominence of curiosity-driven research, as the Ngram of Figure 8 reminds us of the timing.[61]

Conclusion

Curiosity-driven research has remained prominent since 1988. *The Times* editorialised praising scientific curiosity in 1995.[62] In 2008 Helga Nowotny, the doyenne of European science policy, highlighted curiosity in 2008.[63] In 2009, the Royal Society launched a project, first called 'Fruits of Curiosity' that produced the *Scientific Century* publication in 2010; science, it was said, is 'primarily motivated by curiosity'.[64] Paul Nurse, president of the Royal Society in 2014, said: curiosity was the 'main impetus of research', adding that 'top down direction on what science should be done is ineffective'.[65] This pairing, of curiosity and autonomy, is telling. The sociologist Jane Calvert, when interviewing scientists about the meaning of basic research, was struck by an apparent contradiction that took place with little cognitive dissonance.[66] Scientists would say they were free, free to follow curiosity, but then say that their funding sources necessarily directed them.

So what have we learned? If there's one thing we all know about curiosity is that it killed the cat. (In fact, the leading final cause of the death in *Felis catus* is euthanasia – 87% - it wasn't curiosity that killed the cat, it was the vet.[67]) Peter Medawar, in *Advice to a Young Scientist*, noted that while curiosity might kill some cats, it also cured others.[68] Curiosity cured the cat, because veterinary medicine depended, at some level, on science, including curiosity-driven science.

This case of veterinary science is small (and anecdotal) reminder to us of a broader, substantiated fact: that much of modern science has been generated in response to the incessant articulation of problems, whether they be those of human health, armed conflict, civil administration, the building of technological systems, or even the curing of cats. That was the main conclusion of my book, *Science in the Twentieth Century and Beyond*. Science's utility can be its greatest justification, but it is also a social hazard. The invention of kinds of science, from "basic science" to "mission-oriented science" to "curiosity-driven research" has provided important tools used to create and manage the apparent social autonomy that is functional in sustaining science. The social contract has been that science will deliver, if left autonomous.

Curiosity-driven research is a particularly intriguing case. The association of curiosity with childhood, with its attendant connotations of innocence and vitality, which I showed was a recurrent pattern in scientists' autobiographical accounts, is particularly effective at depoliticising the social contract. If we think all children are naturally curious then we think of curiosity as universal and innate. But even the association of curiosity with childhood is in fact surprisingly partial and political. Pollsters in the recent extraordinary US Presidential election used the question 'would you prefer your child to be curious or to show good manners?' and found that it was an excellent predictor of voting intentions.[69]

We have also seen that curiosity-driven science has a long and a short history. Early modern curiosity was deeply ambiguous : a source of sin or virtue. Bacon, and Baconianism as institutionalised in the Royal Society, set it on the path to universal positive. But even then it was part of the rhetorical armoury of science. In the twentieth century curiosity has seemed an uncomplicated and desirable virtue. We saw scientific curiosity rise so high that it was beatified – the "holy curiosity" of Einstein. This instance – in which the *Onion* satirises a situation in which an MIT grad student puts 30% out of a job by a small change to a robotics experiment done 'out of mere curiosity' – is a rare case where curiosity is a negative.[70] It is funny, of course, precisely because of our expectations that scientific curiosity is a good.

Einstein said curiosity 'has its own reasons for existence'. But the short history – the rise to prominence of "curiosity-driven research" since Margaret Thatcher's Royal Society speech of 1988 - should remind us that it is a tool, made and wielded for purposes in this world.

Figure 1. Einstein curiosity memes.

Figure 2. Bernal's map of science, from *The Social Function of Science* (1939).

Figure 3. A detail from Bernal's map of science, showing how biochemistry contributed to the science of food preservation, which in turn solved practical problems of cookery. Note the direction of the arrows. My argument in *Science in the Twentieth Century and Beyond* (2012) is that the influence flows in both directions.

Figure 4. Daniel Berlyne's test for curiosity in infants. From Berlyne (1966), p. 29.

Figure 5. Daniel Berlyne's visual experiments for adults' curiosity prompted by incongruity. From Berlyne (1966), p. 27.

Figure 6. Chart from the United States National Science Foundation's Project TRACES (1968) for the electron microscope case study. Several pathways of science and technology converge to produce an innovation. The (red in the original) circles represent 'nonmission research' and the (green in the original) triangles 'mission-oriented research'. The reader is meant to conclude that considerable nonmission research should be supported to secure later, important inventions.

Figure 7. Project TRACES electron microscope case study (detail): the 'nonmission research' of Einstein and Planck.

Figure 8. Google Ngram for "curiosity-oriented research" (blue in original, the earlier peak) and "curiosity-driven research" (red in original, the later spike), 1900-2010. Ngram generated on 3 April 2017.

Figure 9. List of atmospheric chemistry equations that Margaret Thatcher requested for inspection in the context of discussions of acid rain policy. TNA PREM 19/1217. Chester to Thatcher, 5 June 1984.

Figure 10. Thatcher's distinctive pen (blue in the original) shows what she has highlighted in her prime ministerial papers. Here she has read a report on developments in physics.

[1] Hitoshi Nakatogawa, quoted in Richard Van Noorden and Heidi Ledford, 'Medicine Nobel for research on how cells "eat themselves". Japanese biologist Yoshinori Ohsumi recognized for work on autophagy', *Nature* **538**, 18-19 (6 October 2016).

[2] John Cornforth, Nobel Prize banquet speech, 10 December 1975. http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1975/cornforth-speech.html

[3] Carlo Rubbia, interview, July 2008. https://www.nobelprize.org/nobel_prizes/physics/laureates/1984/rubbia-interview.html. Accessed 3 April 2017.

[4] Phillip A. Sharp, interview with Joanna Rose, 4 December 2001. https://www.nobelprize.org/nobel_prizes/medicine/laureates/1993/sharp-interview.html. Accessed 3 April 2017.

[5] Christiane Nüsslein-Volhard, interview, July 2003. http://www.nobelprize.org/nobel_prizes/medicine/laureates/1995/nusslein-volhard-interview.html. Accessed 3 April 2017.

[6] Venkatraman Ramakrishnan, 'Biographical. From Chidambaram to Cambridge: A Life in Science'. https://www.nobelprize.org/nobel_prizes/chemistry/laureates/2009/ramakrishnan-bio.html. Accessed 3 April 2017.

[7] Anthony Hewish, interview, June 2009. https://www.nobelprize.org/nobel_prizes/physics/laureates/1974/hewish-interview.html. Accessed 3 April 2017.

[8] Struther Arnott, T.W.B. Kibble, Tim Shallice, 'Maurice Hugh Frederick Wilkins, CBE. 15 December 1916 — 5 October 2004', *Biographical Memoirs of Fellows of the Royal Society* **52**, 456-478 (2006), at p. 458. See also: Maurice Wilkins, *The third man of the double helix: the autobiography of Maurice Wilkins* (Oxford University Press, 2003).

[9] George F. Smoot, interview, July 2008. http://www.nobelprize.org/nobel_prizes/physics/laureates/2006/smoot-interview.html. Accessed 3 April 2017.

[10] Leon M. Lederman, interview, December 2001. https://www.nobelprize.org/nobel_prizes/physics/laureates/1988/lederman-interview.html. Accessed 3 April 2017.

[11] Hermann Bondi, 'Curiosity of a scientist' (review of Freeman Dyson, *Disturbing the Universe*', *Nature* **282**, 138-140 (8 November 1979), at p. 138.

[12] Albert Einstein, *Albert Einstein: philosopher-scientist*, Volume 7 of The Library of Living Philosophers, edited by Paul Arthur Schilpp (Library of Living Philosophers, 1949).

[13] 'Death of a genius. His fourth dimension, time, overtakes Einstein', *Time* (2 May 1955), pp. 61-66.

[14] The rather odd use of 'he' in 'he contemplates the mysteries of eternity' refers, in the context of the interview, to the 'man of value', a figure opposed by Einstein to the 'man of success'. The man of value gives more than he receives out of life; the man of success does the opposite.

[15] In addition to 'Never lose a holy curiosity', another common meme quotation is Einstein's 'I have no special talents. I am only passionately curious'. The quotation can be traced to two letters. 'Ich habe keine besondere Begabung, sondern bin nur leidenschaftlich neugierig' (I have no special talents. I am only passionately curious) is in a letter to the biographer Carl Seelig (11 March 1952), Einstein Archives 39-013, Princeton. Similar wording was used in a letter to Hans Muehsam (4 March 1953) Einstein Archives 38-424.

[16] Barbara Benedict, *Curiosity: a cultural history of early modern inquiry* (Chicago: University of Chicago Press, 2001), p. 3.

[17] Benedict, *op. cit.* (note 16), p. 13 for 'dangerous license'. Paula Findlen, *Possessing nature: museums, collecting and scientific culture in early modern Italy* (Berkeley: University of California Press, 1994). Lorraine Daston and Katharine Park, *Wonders and the order of nature, 1150-1750* (New York: Zone Books, 2001).

[18] Francis Bacon, *The advancement of learning* (1603), quoted in Benedict, *op. cit.* (note 16), p. 19.
[19] Benedict, *op. cit.* (note 16), p. 2.
[20] Thomas Sprat, *The history of the Royal Society of London for the Improving of Natural Knowledge* (London: T.R. for J. Martyn at the Bell, 1667), p. 245. My emphasis.
[21] Peter Medawar, *Advice to a young scientist* (New York: Basic Books, 1979), pp. 47-48.
[22] John Wilkins, the seventeenth-century mathematician and natural philosopher who is the Wilkins of 'Wilkins-Bernal-Medawar', would have agreed with the desirability of knowledge being close to practice, as the following quotation, in which he praises Aristotle, makes clear: 'Being so far from esteeming Geometry dishonoured by the Application of it to Mechanical Practices, that he thought it to be thereby adorned, as with curious Variety, and to be exalted unto its natural End. And whereas the Mathematicians of those former Ages, did possess all their Learning as covetous Men to their Wealth, only in Thought and Notion; the judicious Aristotle, like a wise Steward, did lay it out to particular Use and Improvement; rightly preferring the Reality and Substance of Publick Benefit, before the Shadows of some retired Speculation, or Vulgar Opinion'. Note the passing reference to 'curiosity'. John Wilkins, *Mathematical Magick: or the Wonders That May Be Performed by Mechanical Geometry*, 4^{th} edition (Ric. Baldwin, 1691), at pp. 6-7.
[23] Medawar, *op. cit.* (note 21), p. 7.
[24] Medawar, *op. cit.* (note 21), p. 47. Bernal makes the point in *The Social Function of Science* (see below).
[25] Miles Parker, 'The Rothschild report (1971) and the purpose of government-funded R&D—a personal account', *Palgrave Communications* **2**, Article number: 16053 (2016). Jon Agar, 'Thatcher, scientist', *Notes and Records of the Royal Society of London* **65(3)**, 215-232 (2011)..
[26] Medawar, *op. cit.* (note 21), p. 47.
[27] Robert Bud, '"Applied science": a phrase in search of a meaning', *Isis* **103**, 537-545 (2012). Graeme Gooday, '"Vague and artificial": the historically elusive distinction between pure and applied research', *Isis* **103**, 546-554 (2012).
[28] David Edgerton, *Warfare state: Britain, 1920-1970* (Cambridge University Press, 2006).
[29] David Edgerton and Sally Horrocks, 'British industrial research and development before 1945', *Economic History Review* **47**, 213-238 (1994).
[30] Sabine Clarke, 'Pure science with a practical aim: the meanings of fundamental research in Britain, circa 1916-1950', *Isis* **101**, 285-311 (2010).
[31] Benoît Godin, 'Technological Innovation. On the origins and development of an inclusive concept', *Technology and Culture* **47**, 527-556 (2016).
[32] Godin, *op. cit.* (note 30), p. 531.
[33] Frank M. Turner, 'Public science in Britain, 1880-1919', *Isis* **71**, 589-608 (1980).
[34] Clarke, *op. cit.* (note 29), p. 294.
[35] Jon Agar, *Science in the twentieth century and beyond* (Cambridge: Polity, 2012). Jon Agar, 'Working worlds and British science, 1900-1939', forthcoming in *Institutionalisation of Science and the Public Sphere in Modern Britain*, and presented as paper at Aichi Prefectural University, Japan, 25-26 March 2017.
[36] Tim DeJager, 'Pure science and practical interests: The origins of the agricultural research council, 1930–1937', *Minerva* **31**, 129-150 (1993), at p. 136.
[37] See, for his life: Andrew Brown, *J.D. Bernal: the sage of science* (Oxford University Press, 2005).
[38] Thomas Henry Huxley, *Method and results* (London: Macmillan, 1893), quoted in J.D. Bernal, *The social function of science* (London: George Routledge, 1939), p. 95.
[39] Bernal, *op. cit.* (note 37), p. 94.
[40] Bernal, *op. cit.* (note 37), p. 98.
[41] William James, *Principles of psychology* (New York: Holt, 1970, original work published 1890).
[42] Vladimir J. Konečni, 'Daniel E. Berlyne: 1924-1976', *American Journal of Psychology* **91**, 133-137 (1978).
[43] D.E. Berlyne, 'A theory of human curiosity', *British Journal of Psychology* **45**, 180-191 (1954).
[44] D.E. Berlyne, 'Curiosity and exploration', *Science*, New Series **153(3731)**, 25-33 (1966). Currently cited 890 times, according to Google scholar, accessed 3 April 2017.
[45] Berlyne also conducted an experiment where 'subjects were presented with quotations, each followed by the names of two or three possible authors. Each author's name was coupled with a number, purporting to show how many teachers out of a group of 100, had guessed it to be the correct name'. Berlyne thus predicted the early evening BBC TV gameshow *Pointless*.
[46] Ludwig Wittgenstein, *Philosophical investigations* (Oxford: Blackwell, 1953). Thomas Kuhn, *The structure of scientific revolutions* (University of Chicago Press, 1962, second edition 1970), p. 114.

[47] David Cahan, *An institute for an empire: the Physikalisch-Technische Reichsanstalt, 1871–1918* (Cambridge: Cambridge University Press, 1989), p. 146.
[48] Agar, *Science in the Twentieth Century and Beyond*, *op. cit.* (note 34), p. 27.
[49] The National Archives (hereafter TNA) ED 214/84. CSP(Q)(69)1st, 18 March 1969.
[50] TNA ED 214/84. I.C.R. Byatt and A.V. Cohen, 'An attempt to quantify the economic benefits of scientific research', 1969. Published the same year as *Science Policy Studies No. 4*, London: HMSO, 1969. Dr (later Sir) Ian Byatt would become Head of Public Sector Economic Unit (1972–1978), Deputy Chief Economic Adviser (1978–89) at the Treasury, and Director General of Ofwat in the 1990s. Cohen would later join the Health and Safety Executive.
[51] TNA ED 214/84. CSP(Q)(69)1st, 18 March 1969. Involved were Professor Jevons, Mr Pearson, Bernard Leach, Mike Gibbons, J. Langrish, and R.D. Johnston of Manchester University/Manchester Business School, C.F. Carter of Lancaster University, Chris Freeman of SPRU at Sussex University, and K. Binning and R.D. Medford of the Programmes Analysis Unit (PAU) of MinTech (later DTI)/UKAEA. Professor Wolfe, Professor Youngson and David Edge of Edinburgh University, as well as Rom Harré of Linacre College, Oxford, were held as "reserves".
[52] TNA ED 214/86, Jevons and Pearson, 'Feasibility study of the method proposed by Byatt and Cohen for quantifying the economic benefits of scientific research', September 1969. They added the rider, however: 'it should be emphasised that we do NOT conclude that curiosity-oriented research is useless in economic terms. On the contrary, in view of the importance of the problem, we feel that further work should be directed to exploring various avenues through which curiosity-oriented research may lead to economic benefits'.
[53] TNA AB 15/7735. R.D. Medford, 'Curiosity-oriented research: an experimental study: X-ray crystallography', London: HMSO (1974).
[54] TNA PREM 19/1369. Nicholson to Thatcher, 2 May 1984. This categorisation of science was used by bodies such as the ABRC.
[55] PREM 19/1369. Nicholson to Thatcher, 6 March 1984. My emphasis.
[56] Max Perutz, 'How to stifle research', *New Scientist* (10 December 1987), p. 57. Tam Dalyell asked the government for a response via a question in Parliament in January 1988. TNA ED 34/311. Tam Dalyell question to Secretary of State for Education and Science, 19 January 1988. Perutz's anger was directed at the Advisory Board for the Research Councils (ABRC) report, *A strategy for the science base* (May 1987).
[57] TNA PREM 19/2478. Annotated copy of Max Perutz, 'How to stifle research', *New Scientist* (10 December 1987), p. 57.
[58] TNA PREM 19/2479. Guise to Thatcher, 25 May 1988. He says here explicitly that he favours the Perutz approach to that of David Philips and Francis Tombs, the chairs respectively of the Advisory Board for the Research Councils (ABRC) and the Advisory Council on Science and Technology (ACOST).
[59] Jon Agar, '"Future forecast—changeable and probably getting worse": the UK government's early response to anthropogenic climate change', *Twentieth Century British History* **26(4)**, 602-628 (2015).
[60] Margaret Thatcher, 'Speech to the Royal Society', 27 September 1988. Copy of the text (as prepared rather than as spoken), can be found in the online archives of the Margaret Thatcher Foundation. http://www.margaretthatcher.org/document/107346. Accessed 3 April 2017. Thatcher's third point is very pertinent to current Brexit times: 'My third point is that, despite an increase in the basic science budget of 15 per cent in real terms since 1979, the United Kingdom is only able to carry out a small proportion of the world's fundamental research and that of course is true of most countries. It is therefore very important to encourage our own people to be aware of the work that is going on overseas and to come back here with their broadened outlook and new knowledge. It is also healthy to have overseas people working here'.
[61] For another view, see: Richard Phillips, 'The impact agenda and geographies of curiosity', *Transactions of the Institute of British Geographers* **35**, 447-452 (2010).
[62] 'March towards zero', *The Times* (17 May 1995), editorial, p. 15.
[63] Helga Nowotny, *Insatiable curiosity: innovation in a fragile future* (Cambridge, MA: MIT Press, 2008).
[64] Royal Society, *The scientific century: securing our future prosperity* (London: Royal Society, 2010), p. 11.
[65] https://www.wadham.ox.ac.uk/news/2014/october/curiosity-led-science
[66] Jane Calvert, 'What's special about basic research?', *Science, Technology, & Human Values* **31**, 199-122 (2006), p. 205:. 'This behavior was also apparent in respect to autonomy, which, as noted above, is central to the history of basic research. Autonomy is closely related to the intentional definition of "basic research" because to do curiosity-driven research, the scientist's autonomy over the research agenda would appear to be a necessary requirement. However, surprisingly many of the scientists I interviewed, who described themselves as basic researchers, admitted that in practice their autonomy was limited. They would often initially maintain that they had complete autonomy in their work and then go on, when considering grant

applications, for example, to admit that they did not have so much. One scientist, when I asked him how much freedom he had, answered, "100%. I can do whatever I want," but then quickly added, "that's a bit facetious because I do what the federal government, what the NIH [National Institutes of Health] funds me to do" (U.S. biologist)'.

[67] http://skeptvet.com/Blog/2015/03/longevity-causes-of-death-in-pet-cats/

[68] '"Curiosity killed the cat" is an old nanny's saying, though it may have been that same curiosity which found a remedy for the cat on what might otherwise have been its deathbed'. Medawar, *op. cit.* (note 21), p. 7.

[69] https://www.washingtonpost.com/news/wonk/wp/2016/02/01/how-your-parenting-style-predicts-whether-you-support-donald-trump/?utm_term=.aedb309a88cb. Thanks Alan Finlayson for this source.

[70] '"What if we try this?" asks robotics grad student about to eliminate 30% of workforce', *The Onion* (22 February 2017). http://www.theonion.com/article/what-if-we-try-asks-robotics-grad-student-about-el-55347.

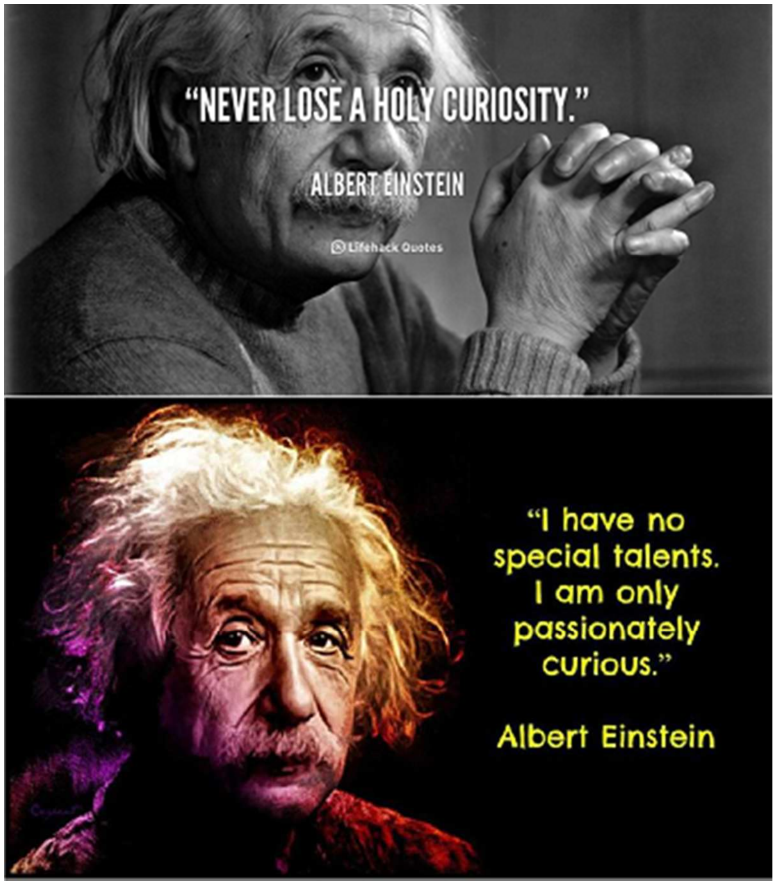

Figure 1. Einstein curiosity memes.

101x115mm (96 x 96 DPI)

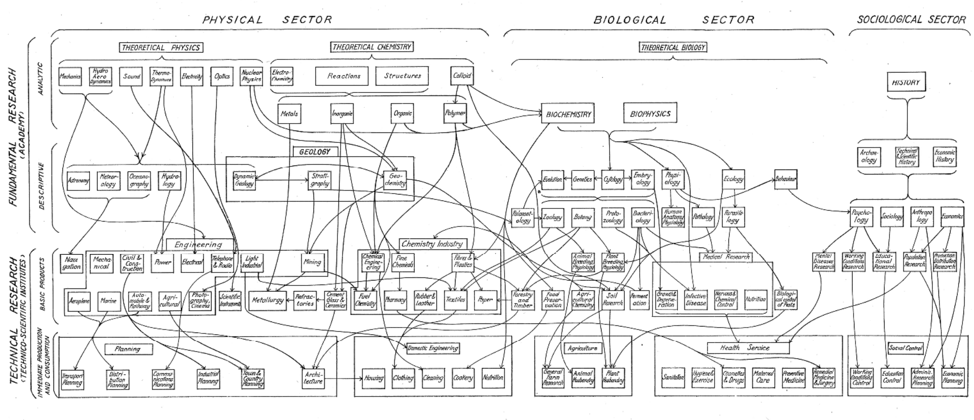

Figure 2. Bernal's map of science, from The Social Function of Science (1939).

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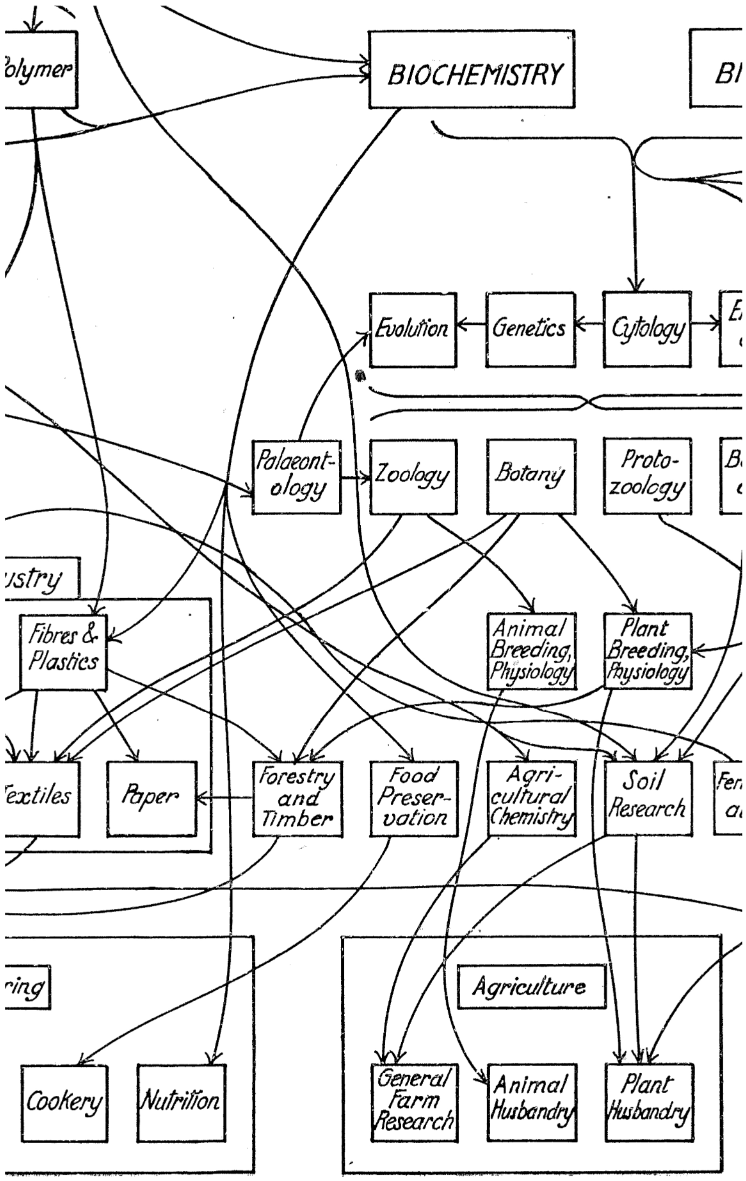


Figure 3. A detail from Bernal's map of science, showing how biochemistry contributed to the science of food preservation, which in turn solved practical problems of cookery. Note the direction of the arrows. My argument in Science in the Twentieth Century and Beyond (2012) is that the influence flows in both directions.

550x809mm (96 x 96 DPI)

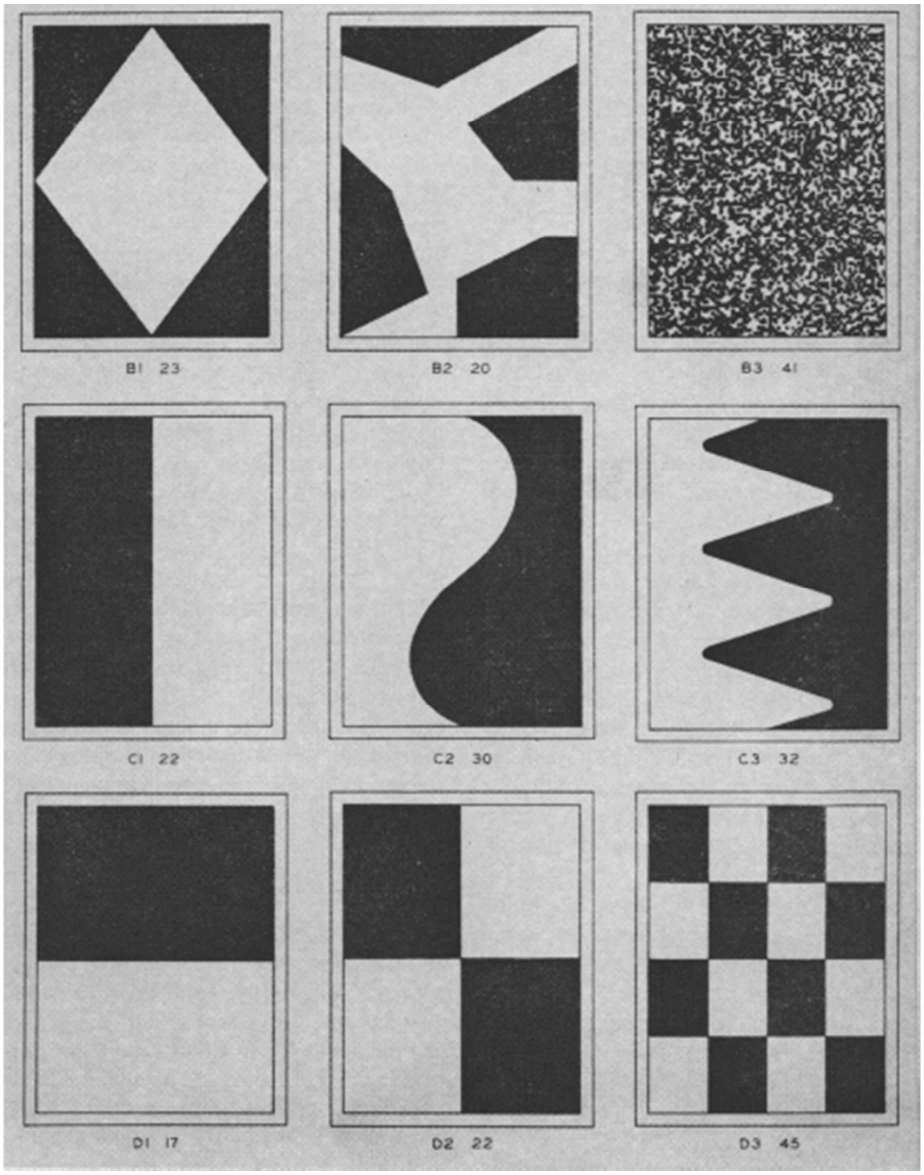
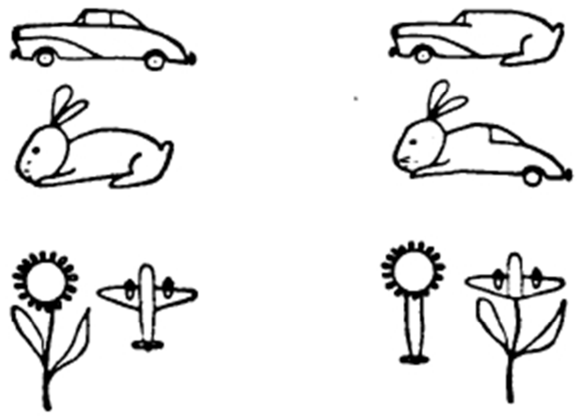


Figure 4. Daniel Berlyne's test for curiosity in infants. From Berlyne (1966), p. 29.

121x154mm (96 x 96 DPI)



F. INCONGRUOUS JUXTAPOSITION

Figure 5. Daniel Berlyne's visual experiments for adults' curiosity prompted by incongruity. From Berlyne (1966), p. 27.

104x75mm (96 x 96 DPI)

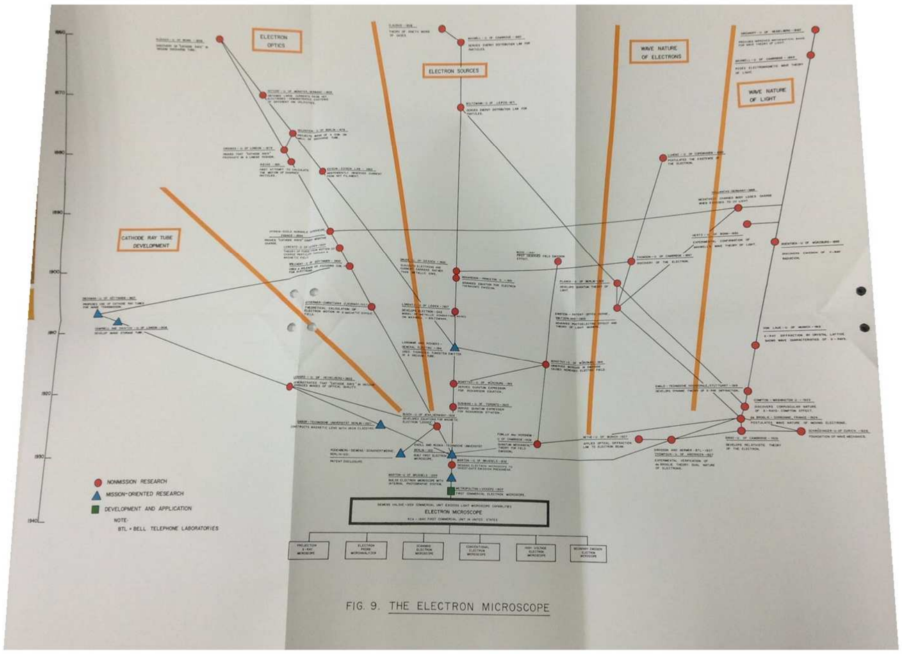


Figure 6. Chart from the United States National Science Foundation's Project TRACES (1968) for the electron microscope case study. Several pathways of science and technology converge to produce an innovation. The (red in the original) circles represent 'nonmission research' and the (green in the original) triangles 'mission-oriented research'. The reader is meant to conclude that considerable nonmission research should be supported to secure later, important inventions.

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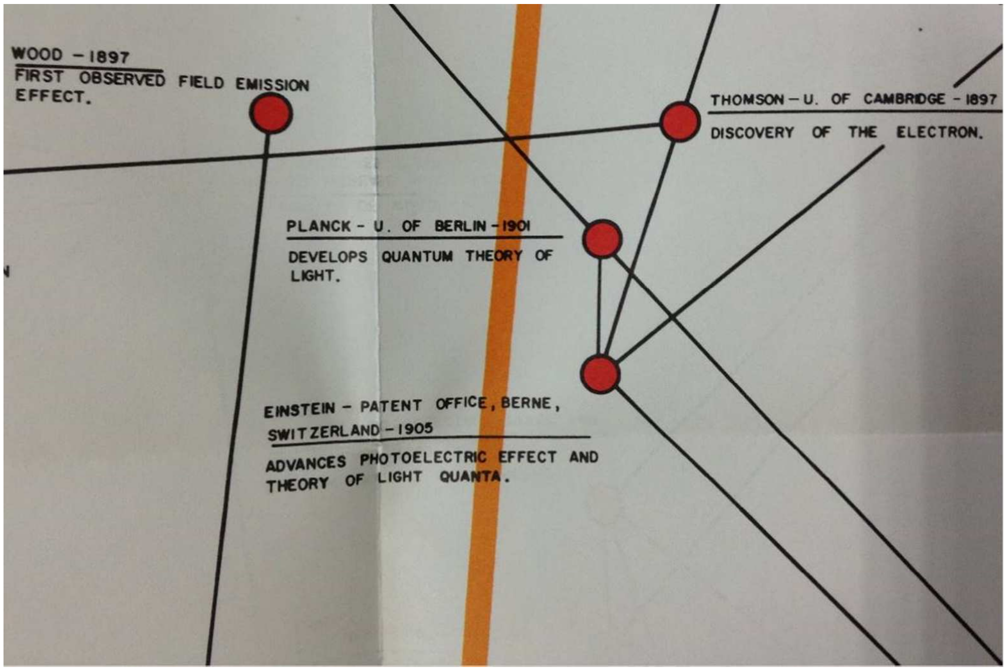


Figure 7. Project TRACES electron microscope case study (detail): the 'nonmission research' of Einstein and Planck.

255x190mm (117 x 104 DPI)

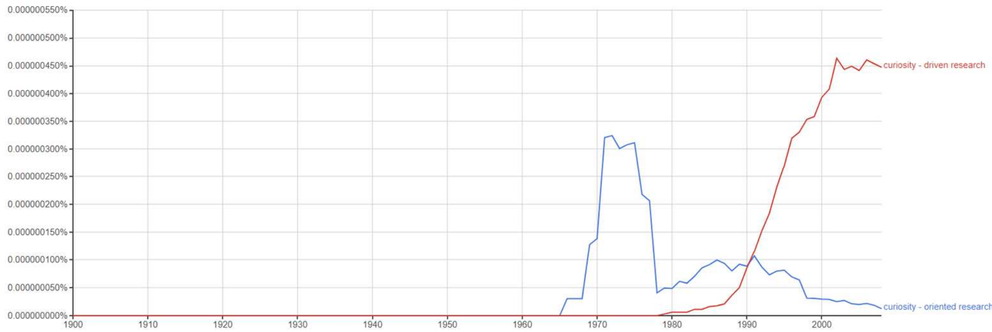
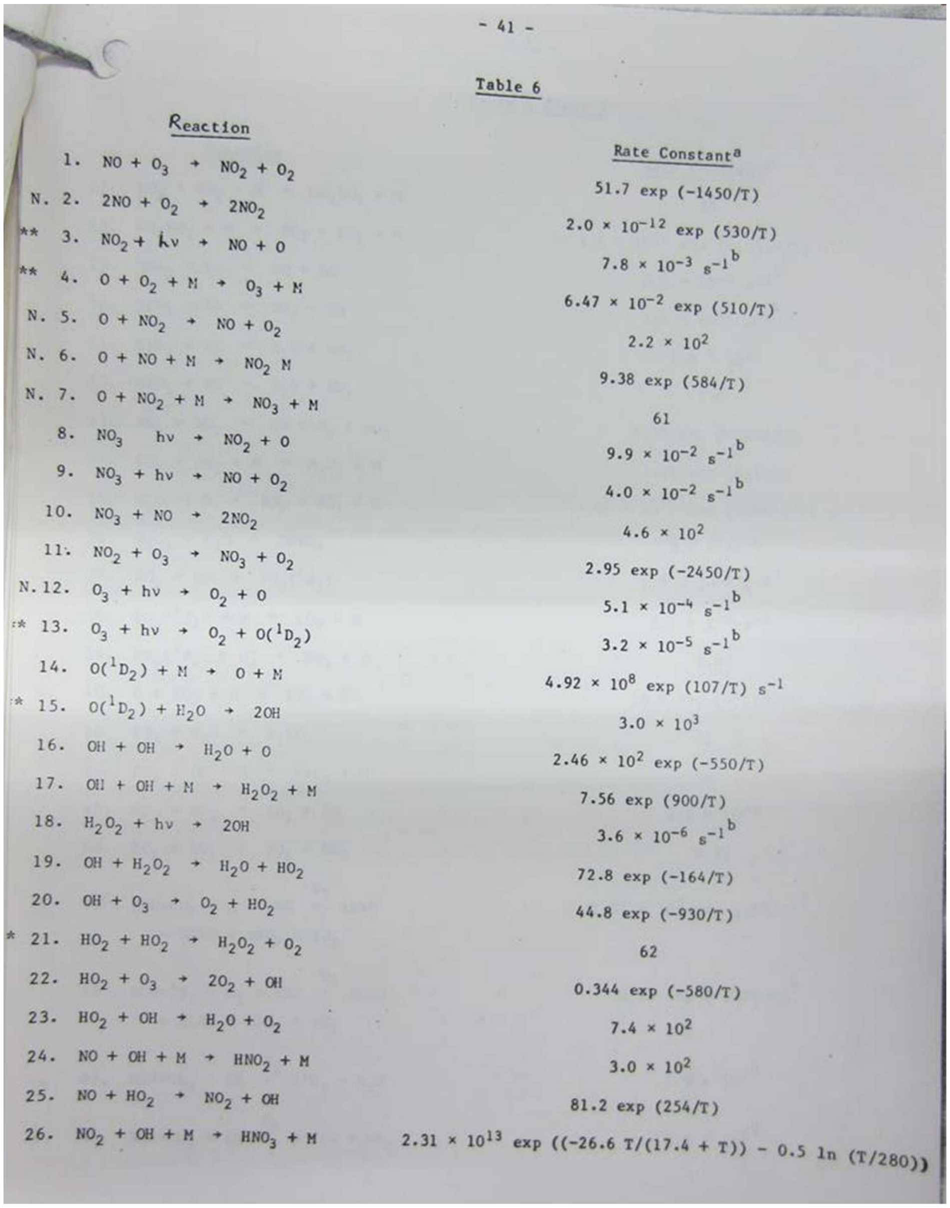


Figure 8. Google Ngram for "curiosity-oriented research" (blue in original, the earlier peak) and "curiosity-driven research" (red in original, the later spike), 1900-2010. Ngram generated on 3 April 2017.

445x149mm (96 x 96 DPI)



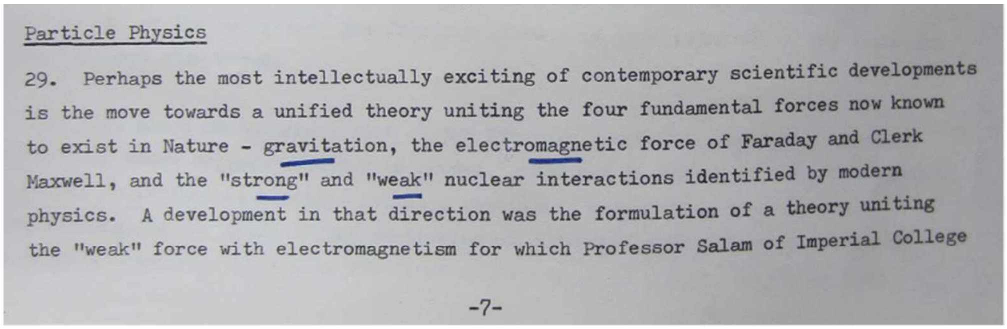
- 41 -

Table 6

Reaction	Rate Constant[a]
1. $NO + O_3 \rightarrow NO_2 + O_2$	51.7 exp (-1450/T)
N. 2. $2NO + O_2 \rightarrow 2NO_2$	2.0×10^{-12} exp (530/T)
** 3. $NO_2 + h\nu \rightarrow NO + O$	$7.8 \times 10^{-3}\ s^{-1}$ [b]
** 4. $O + O_2 + M \rightarrow O_3 + M$	6.47×10^{-2} exp (510/T)
N. 5. $O + NO_2 \rightarrow NO + O_2$	2.2×10^{2}
N. 6. $O + NO + M \rightarrow NO_2\ M$	9.38 exp (584/T)
N. 7. $O + NO_2 + M \rightarrow NO_3 + M$	61
8. $NO_3\ \ h\nu \rightarrow NO_2 + O$	$9.9 \times 10^{-2}\ s^{-1}$ [b]
9. $NO_3 + h\nu \rightarrow NO + O_2$	$4.0 \times 10^{-2}\ s^{-1}$ [b]
10. $NO_3 + NO \rightarrow 2NO_2$	4.6×10^{2}
11. $NO_2 + O_3 \rightarrow NO_3 + O_2$	2.95 exp (-2450/T)
N. 12. $O_3 + h\nu \rightarrow O_2 + O$	$5.1 \times 10^{-4}\ s^{-1}$ [b]
** 13. $O_3 + h\nu \rightarrow O_2 + O(^1D_2)$	$3.2 \times 10^{-5}\ s^{-1}$ [b]
14. $O(^1D_2) + M \rightarrow O + M$	4.92×10^{8} exp (107/T) s^{-1}
** 15. $O(^1D_2) + H_2O \rightarrow 2OH$	3.0×10^{3}
16. $OH + OH \rightarrow H_2O + O$	2.46×10^{2} exp (-550/T)
17. $OH + OH + M \rightarrow H_2O_2 + M$	7.56 exp (900/T)
18. $H_2O_2 + h\nu \rightarrow 2OH$	$3.6 \times 10^{-6}\ s^{-1}$ [b]
19. $OH + H_2O_2 \rightarrow H_2O + HO_2$	72.8 exp (-164/T)
20. $OH + O_3 \rightarrow O_2 + HO_2$	44.8 exp (-930/T)
* 21. $HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	62
22. $HO_2 + O_3 \rightarrow 2O_2 + OH$	0.344 exp (-580/T)
23. $HO_2 + OH \rightarrow H_2O + O_2$	7.4×10^{2}
24. $NO + OH + M \rightarrow HNO_2 + M$	3.0×10^{2}
25. $NO + HO_2 \rightarrow NO_2 + OH$	81.2 exp (254/T)
26. $NO_2 + OH + M \rightarrow HNO_3 + M$	2.31×10^{13} exp ((-26.6 T/(17.4 + T)) - 0.5 ln (T/280))

Figure 9. List of atmospheric chemistry equations that Margaret Thatcher requested for inspection in the context of discussions of acid rain policy. TNA PREM 19/1217. Chester to Thatcher, 5 June 1984.

134x170mm (150 x 150 DPI)



Particle Physics

29. Perhaps the most intellectually exciting of contemporary scientific developments is the move towards a unified theory uniting the four fundamental forces now known to exist in Nature - gravitation, the electromagnetic force of Faraday and Clerk Maxwell, and the "strong" and "weak" nuclear interactions identified by modern physics. A development in that direction was the formulation of a theory uniting the "weak" force with electromagnetism for which Professor Salam of Imperial College

-7-

Figure 10. Thatcher's distinctive pen (blue in the original) shows what she has highlighted in her prime ministerial papers. Here she has read a report on developments in physics.

219x71mm (150 x 150 DPI)