Public Understanding of Science

A history of communicating scientific ideas

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Routledge Studies in the History of Science, Technology and Medicine

First published 2006
by Routledge
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

Simultaneously published in the USA and Canada
by Routledge
270 Madison Ave, New York, NY 10016

Routledge is an imprint of the Taylor & Francis Group, an informa business
This edition published in the Taylor & Francis e-Library, 2006.

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British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging in Publication Data
A catalog record for this book has been requested

ISBN13: 978-1-134-62499-7 ePub ISBN
ISBN10: 0-415-20638-3 (hbk)
ISBN10: 0-203-96642-2 (ebk)
ISBN13: 978-0-415-20638-9 (hbk)
ISBN13: 978-0-203-96642-6 (ebk)

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Acknowledgements

This book could not have been written without help from librarians, especially in Durham University and at the Royal Institution in London. I am grateful to my colleagues in Durham, for support during a term of research leave during which the book was begun, and then subsequently during my process of retirement when it was completed. I am also grateful to friends and colleagues who have listened to papers at conferences and seminars on history of science, from which chapters here have evolved; to Durham University for appointing me to chair its ethics committee for several years; and to the Royal Society of Chemistry, which has elected me to its Committee for the Promotion of Chemistry to the Public – both of these being most instructive experiences. Students in Durham met much of this book as a course on the emergence of two cultures, and I am grateful for their reactions in tutorials.

The author and publishers would like to thank the following for g[illegible] produce material in this work: [illegible] *ce Reviews* for permission to reprint a v[illegible] etry, metaphor and algebra', previously p[illegible] Davy the Poet', by David Knight in *I*[illegible] *Reviews*, December 2005 (Vol. 30, number 4, pp. 356–72).

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Understanding

Science is not easy to understand. And sometimes it is like an ice-dance show: at first you wonder how it's done, and then you wonder why. It is not obvious why people devote themselves to this activity, or why others should be interested and should directly or indirectly pay the bills. This book is about how people have tried to get natural science (physics, chemistry, biology) loved – or sometimes hated, for just as we all find out about religion not only from bishops, rabbis or ayatollahs, so with science the heretics and opponents can teach us as much as the academicians and professors. Mainstream 'popular science' often implies a reductive scientism,[1] the notion that real explanations of anything must always be scientific in the way physics is, and a certain condescension to meaner intellects. It is also full of 'breakthroughs', good for promoting funding and careers, but often of little lasting significance: promises of a world where science and technology will abolish poverty and pain were new and exciting when Humphry Davy made them in his inaugural lecture in London in 1802,[2] but have been often broken since. Just as churches have not always practised the love they preach, so peace and plenty have not always resulted from the open-minded search for truth prominent in scientists' sermons. Mavericks too, promising what contemporaries said was impossible, have always been around to damn the complacent scientific establishment.[3]

Science wars are thus not new. There have always been critics, for some of whom scientists have been comically absent-minded intellectuals, while for others they have been sinister Dr Strangeloves: and polemic against science is as instructive as propaganda for it, and equally enthusiastic. Critics may have some vision of a pre-scientific world we have lost, an Eden, Merrie England or Jeffersonian rural America; or want to leave room for religious or other beliefs, and for humanities, in what seems a cold inanimate world; or may have in mind a scientific world-view, or 'paradigm', different from the current one. Thus two rather dissimilar people, both of them in their different ways enthusiasts for science, rejected mechanical, clockwork analogies widely held around 1800 in favour of a world of forces, with dynamic rather than inert matter: Michael Faraday proposed field theory[4] in place of atoms and action at a distance; and the poet Samuel Taylor Coleridge, while excited by the chemistry of his friend Davy,[5] rejected its claims to account for the processes of life.[6]

We should remember also that much science is rather dull, as those who have studied it formally will know. Doing experiments like putting pennies into concentrated nitric acid and watching the brown fumes, or making gas jars full of hydrogen go pop with a lighted splint, is fun; and so is squirting other people with wash-bottles. But making accurate measurements, weighing things and working steadily through analytical procedures is unexciting; and learning much chemistry is painful, with hard names, complex formulae, and equations difficult to balance. Just so, thinking up hypotheses is fun, but processes of confirmation or refutation are slow, laborious and often involve statistics. That is hard to popularise. Proof is a burden. The science that gets picked up is the glamorous, the sublime perhaps or the manifestly practical; or it is the controversial.

Science has long been associated with great rows.[7] Isaac Newton quarrelled with some of his notable contemporaries, Robert Hooke, John Flamsteed and Gottfried Wilhelm Leibniz. In science, priority really matters: it is a race in which there are no silver or bronze medals. In the nineteenth century, the two leading men in any particular field were very frequently at daggers drawn, with their disciples or scientific children being dragged in like young Capulets or Montagues. Thus in geology, Adam Sedgwick and Roderick Murchison fell out over whether Sedgwick's Cambrian rocks were really just the lower part of Murchison's Silurian; in zoology, Richard Owen and Thomas Henry Huxley quarrelled publicly over topics like the anatomy of the gorilla's brain (and its similarity to ours); and in chemistry, James Dewar and William Ramsay were not on speaking terms, and so Ramsay had to reinvent apparatus suitable for liquefying gases when he isolated argon, neon, krypton and the other 'noble gases' from the atmosphere.[8] It was no better in France, Germany or the USA; and not entirely different in today's bigger scientific world. Public disputes make science a good spectator-sport. There has thus often been an entry into current science through personalities and issues, much more exciting than colder and more formal routes; and there are always scientists who also enjoy playing to a gallery, though others tut-tut at dirty washing being done in public, rather than questions being resolved among experts.

Popular science at any time is therefore for many reasons different from the established kind; and, to the frustration of scientists, public understanding (just like public interest) is very different from theirs. There is no one 'public' after all. Thus there are specialists in different disciplines who want to keep up across the board. They may be supportive of colleagues, or may feel that some sciences are grossly and unfairly over-funded compared to theirs. Then there are other highly-educated people, in humanities, languages, law or social science, 'erudite non-specialists' they have been called, who are again thrilled, intrigued or horrified at what they perceive going on in science. These may be policy-makers, journalists, legislators and others whose opinions are directly important to scientists, and affect their lives. Distinct from these are ordinary people, busy, more or less curious about new ideas or enthusiastic about technical developments, probably suspicious about what supposed experts tell them, and wary of change. There are consumers to be stimulated by scientific-looking advertisements to buy beauty products or pep pills – or to avoid 'chemicals' in the name of nature and the organic. Finally, there are children, the rising generation, whose inquisitive enthusiasm must be maintained if science is to go on. Museums used to be aimed at the more earnest of such publics: nowadays having a good time is more crucial, and 'things', historic exhibits that can give a wonderful feel for the development of the sciences and engineering, may be put in storage so that visitors can play interactive computer games. The balance is not obvious; and to appeal to several publics at once is and was problematic. It matters, because of the place that science holds in our culture and our economies.

The problems became apparent in the long nineteenth century, the 'Age of Science' (when it came to maturity[9]) from the French Revolution of 1789, spurred on supposedly by the intellectuals of the Enlightenment, to the outbreak of the First World War ('the chemists' war') in 1914. The classic work on this period, published a century ago, was John Theodore Merz's *History of European Thought in the Nineteenth Century*, of which the first two volumes were devoted to science.[10] We are all in debt to this German-born and trained electrical engineer who made his fortune in Newcastle. His book was thematic, getting inside the minds of scientists in various traditions: so is mine, but concerned with the outside – looking at various ways in which science was made available to various publics, and sometimes to everyone: in sermons, lectures, verses, pictures, ballyhoo, displays, travellers' tales, journalism at various levels, and then later in the century from newly professional biologists and physicists – and professional popularisers. Some of these attempts to improve understanding were solemn, but in many the aim was to make it fun; and this book will fail if it is not 'entertaining knowledge' also. It is serious too: what was perceived or even generally supposed is as interesting and important, after all, as what happened among insiders.

The nineteenth century saw, in physiology, chemistry, geology and thermodynamics, as well as in technology, the delayed triumphs of the scientific revolution of Galileo and Newton; but also the emergence of experts who no longer shared one common culture – professionally trained scientists, engineers, doctors, nurses, architects, accountants, lawyers, clergy, and even writers and journalists. Renaissance science had been introduced into Europe through contacts with Islam and China: modern science, which became essentially an activity for comfortably off European males, was then opened up during the nineteenth century. It became a route to social mobility. Women's activity, and that of assistants at home, and in the field or the outback, became less covert. By 1900 skilled practitioners were also emerging in India and Japan, and the USA was on the way to becoming a scientific superpower.

In late-eighteenth-century France it was possible to contemplate a career in science, culminating in salaried membership of the Academy of Sciences,[11] though only very few could hope to achieve it. France, meaning Paris, remained the world's centre of excellence in science right through the Revolution, the Terror, the Directory, the Consulate, Napoleon's Empire, and the subsequent Bourbon Restoration after the Battle of Waterloo in 1815 and the Congress of Vienna that followed it. The Academy of Sciences was briefly closed down as elitist but soon restored, mildly purged, because it was useful – advising on projects such as the melting of church bells into guns. The eminent chemist Antoine Francois Fourcroy made a great name for himself as a public lecturer,[12] attracting enormous audiences at a time when it was politically necessary for science to be made accessible; while at the Jardin des Plantes and its associated museum and zoo, Georges Cuvier and others also gave public lectures on natural history.[13] Science in the capital was effectively popularised by academicians, experts who certainly did not at that time lose kudos by undertaking such tasks. It was the duty of the natural philosopher to communicate his knowledge and world-view as widely as possible; certainly beyond the narrow confines of the scientific community.

In Britain, undergoing the Industrial Revolution which made possible the victory over France, science was more like a hobby than a career. Water frames, spinning jennies and even steam engines did not draw much upon recent or recondite science. Indeed, technological achievements gave rise to scientific problems. The steam engine did more for science than science did for the steam engine: thermodynamics, the study of heat and work, was born from scientific and mathematical analyses of engines, ideal and actual; and the engineers like Thomas Newcomen, James Watt, Richard Trevithick and George Stephenson who built stationary and then locomotive engines had little formal modern science to guide them. Men of science were often doctors like Thomas Garnett and Thomas Young, clergymen like Gilbert White and Joseph Priestley, lawyers like William Grove, or leisured gentry like Henry Cavendish.

Davy, who abandoned a medical training for chemical research and lecturing, was one of the very few who could make a living from science; and even he, like Dick Whittington, completed his social mobility by marrying money. His attention was called to coal mining by a disastrous explosion near Sunderland. Davy's safety lamp for coal miners, resulting in 1815 from a rapid series of experiments done on the explosive 'fire damp' (methane, our CH_4) in the laboratory of the Royal Institution, was one of the very first examples of 'applied science'. The device invented by the genius in the metropolis worked down the pit, saving lives and making possible the expansion of the coal industry that fuelled the British economy right through the Victorian period and beyond.[14] Davy became Sir Humphry, but his rich marriage was childless – there was no son to inherit his title. His lectures, a sensational success in Regency London, and then his practical discovery, were important in getting science across: useful, entertaining, exciting and now also British.

A lamp not unlike Davy's had been made by classic trial and error by George Stephenson, but the publicity machine of the Royal Society, the Royal Institution and the metropolis generally, was very effective. Men of science in Davy's time were called 'natural philosophers', or 'philosophers' for short: their way was what Davy called 'refined common sense' (and what Huxley was to call 'trained and organised common sense') in approaching problems systematically and from first principles.[15] Thus Davy had identified the fire-damp chemically, and explored its properties: this was contrasted to the unenlightened commonsensical approach of practical men involved in the Industrial Revolution. Davy, it was claimed, had come to his lamp 'philosophically'. Such triumphs of applied science were what he had promised in his inaugural lecture, seeing the dawn of a bright day of high technology – in accordance with Francis Bacon's dictum, 'knowledge is power'. By 1815 laboratory science was becoming ever more recondite. If it was beginning to deliver benefits, popularisers could emphasise that aspect as they sought public interest and acclaim, and funds to make careers. Scientists duly achieved honour and respect; though some could still be viewed as absent-minded and dotty professors, and others as threatening.

Davy, Faraday (his assistant and great discovery), Fourcroy and Cuvier were great men getting across their own work and that of their peers. As natural philosophers, that was the right thing to do; and the snobbery about showmanship that downgraded the writing of textbooks or popularisations, and the giving of public lectures, came only at the end of the nineteenth century, and in the twentieth.[16] The line between experts and popularisers was fuzzier than it later became: the scientific community was very small, and papers published by the Royal Society in its *Philosophical Transactions* about 1800 were discursive and accessible compared to those appearing a century later. The Fellows of the Society, whose subscriptions kept it afloat, were chiefly landed or professional men (no women until after the Second World War) interested in science, but not active in research or teaching. A minority even of the governing Council had ever published a scientific paper until after Davy became President in 1820; and it was another generation before the Society began to look more like an Academy, composed exclusively of distinguished discoverers. Addressing such a body before about 1850 was not so very different from writing or lecturing for the general well-educated public.

Just as literature had its Grub Street hacks, lice on the locks of literature, so there were some who made their living out of getting science across. Thus Jeremiah Joyce,[17] an ardent radical arrested and charged with high treason in the jittery year 1794, was a Unitarian minister among whose many publications was *Scientific Dialogues*, 1807: a favourite of the young John Stuart Mill,[18] who never remembered ‘being so wrapped up in any book’, until his formidable father found out, and drew attention to its errors. Reginald Heber, Bishop of Calcutta in the 1820s, found it in use in a regimental school for English and Indian boys in Cawnpoor, but ‘the native boys … had [it] for their single class-book, which they stammered over by rote, but could none of them construe into Hindostanee’. It was odd that a book written to make science intelligible should have been thus incomprehensible. Joyce also published his lectures on science, and many other works, including an updated edition of William Paley’s celebrated *Natural Theology*; some of his writings were pseudonymous.

Mill was recommended instead to the writings of his father’s early friend and schoolfellow, Thomas Thomson, whose position in the world of science, and target public, were rather different. In his standard textbook of chemistry (which received the accolade of translation into French, the language of Lavoisier), he first made known the atomic theory of John Dalton. He did experiments confirming it, and he ended his career as Professor of Chemistry at Glasgow University, where he made his students do practical work in the laboratory.[19] But there were other popular writers of higher repute than Joyce: Samuel Parkes, an industrial chemist in East London, wrote a very popular *Chemical Catechism*; and the *Conversations on Chemistry* of Jane Marcet, wife of a prominent doctor, also first published in 1807, was specifically aimed at girls, though young Faraday became its most eminent reader.[20]

William Nicholson was more like Thomson in reputation, author of both a dictionary and a textbook of chemistry, and also a translator of scientific works from the French, notably Fourcroy. When Alessandro Volta's paper, in French, announcing the invention of his 'pile' (the ancestor of our electric batteries), was sent to the Royal Society in 1799, Nicholson and the surgeon Anthony Carlisle read it before publication and repeated the experiment. They then extended it, dipping the wires from the terminals into water and observing that hydrogen and oxygen came bubbling up. They were thus among the founders of electrochemistry. Meanwhile, Nicholson had started a *Journal of Natural Philosophy, Chemistry and the Arts* ('arts' meaning 'techniques') in 1797, which ran until 1813, in which year Thomson began his *Annals of Philosophy*, which continued until 1826. Both were swallowed by the *Philosophical Magazine*, edited by Alexander Tilloch, which eventually played an important part in the history of the company, Taylor and Francis, that became its publishers, and which still continues.[21] Tilloch's importance is as an editor and publisher, rather than for any science of his own; and such people have always been of immense importance in the dissemination of science, public knowledge that requires writers, readers, editors and entrepreneurs commissioning and publishing.[22]

These three private journals were aimed at a general readership. Like the Royal Society's more august publication (on excellent paper in quarto size), their crowded octavo volumes covered the whole of science, or most of it, since natural history already had its own vehicles. They included original papers, sometimes important ones, with reprints, news, reviews and correspondence, building up and encouraging a community of readers; and they came out quarterly, without much worry about peer review, thus promising rapid publication to ensure priority.

By 1900, everything was very different. Much more science was known. It had taken Priestley, or later Davy, a few months to pick up enough knowledge to work at the very frontier of knowledge. That was impossible in the days of J.J. Thomson, Marie Curie and Max Planck. Steady development in scientific education, notably from Germany where Justus Liebig at Giessen had invented the research student, working for a PhD, had led to a big and specialised scientific community. The Prussian victories over Austria and then, in 1870, over France had immensely stimulated education in Britain and elsewhere. The perception was that, in 1870, the more educated nation had beaten what had been supposed a much stronger military power. Elementary schooling became compulsory in backward England, and new 'redbrick' universities began to attract students, many of whom took degrees in science or engineering. Universities became centres of scientific research, and the old idea that all students should receive the same basic liberal education (in classics, with maybe mathematics) disappeared. By 1900, there was a network of polytechnics, based upon the German Technisches Hochschulen and ultimately upon the elite Parisian École Polytechnique. Industry, which in Britain especially had been suspicious of book-learning rather than experience, and had employed scientists as consultants when something went wrong, had (in a trend beginning in Germany) become an important employer.[23]

If Charles Snow was right in diagnosing 'two cultures', mutually incomprehensible and perhaps antagonistic, in Britain in the mid-twentieth century (a scientific and a humanistic one), then this situation had been coming about since the later nineteenth century.[24] He found that music was the favourite art of scientists: maybe that was true for the twentieth century, but in the nineteenth it was not obviously the case. We shall be looking at scientific and technical illustration, handsome as well as informative. Faraday admired the visual arts, John Herschel and Henry de la Beche were adepts with a pencil, and the wealthy and cantankerous astronomer Richard Sheepshanks made a wonderful collection of modern paintings, which he bequeathed to the Victoria and Albert Museum. Similarly, Richard Owen, Thomas Huxley and William Clifford loved poetry, and Davy, Herschel and Maxwell wrote it.

We may also doubt Snow's analysis into only two cultures, knowing that chemists and physicists often glowered at each other across a social and intellectual frontier, that historians and literary critics often had little to say to each other, and that social scientists were out on their own. But that only goes to show how fragmented the world of knowledge had become by 1914. Being a 'Renaissance man' was no longer possible. The educated gentleman could not, as Aristotle had hoped, know enough to be able to judge what experts were up to. The brothers Willhelm and Alexander von Humboldt between them knew and contributed to most branches of the knowledge of the early nineteenth century; but by the early twentieth, even such a talented pair could not have done it. Willy-nilly, the world had become specialised: people knew more and more about less and less. Snow was in a line from distinguished Victorians, including William Whewell, the know-all Master of Trinity College, Cambridge, (science his forte, omniscience his foible) who had deplored this trend but could not stop it. Liberal education and common culture were in jeopardy.

The new universities, and even the old ones, admitted women, who could at last come to play a full and public part in science, as they long had in its translation and popularisation: so that the term 'man of science' that had by 1870 generally superseded 'natural philosopher' was in its turn replaced by 'scientist', which Whewell had coined in 1833 by analogy with 'artist', but was slow to gain favour. Spending a life in science, which had been an odd thing to think of in 1800, had become by 1900 a respectable and plausible ambition. Science was, as it had not been in William Blake's day, 'considered to be an inevitable or even necessary way of investigating and understanding the world'.[25] Culture and the economy depended upon it, and ignorance or distaste was beginning to seem shameful.

In 1904 the British Association for the Advancement of Science met in Cambridge, and the President was the Prime Minister, the Conservative Arthur Balfour, a wealthy philosopher and aesthete. He gave an interesting address, calling attention to the great intellectual revolution going on in physics which confirmed his view that science, like everything else, rested upon metaphysical beliefs that were not directly testable. He had been well briefed, but was a man who took a genuine and keen interest in science, and was in the 1920s to become in effect Britain's first Minister for Science, having declined to be nominated as President of the Royal Society. That such a central figure in the establishment should preside at such an occasion was a sign of the full acceptance of the cultural as well as economic importance of science.

Lord Rayleigh, Thomson's predecessor at the Cavendish Laboratory at Cambridge, distinguished for his precision in measurement, had coached Balfour; but most people lacked such distinguished relatives, and were not in Balfour's exalted position. They might hear lectures about science, now illuminated by electricity rather than gas, at the annual meetings of the B.A.A.S., at the Royal Institution in London's West End, or at one of the Literary and Philosophical Societies, Athenaeums, Museums, or Mechanics' Institutes elsewhere. These would be directed at an interested audience, perhaps a well-off and well-educated one, but perhaps composed of working men (a group Huxley particularly liked to address). One aspect of specialisation was that scientists often did not know what their fellows were up to. High-level popularisation, haute vulgarisation, was required to keep physicists aware of developments in biology and so on. Faraday introduced 'Friday Evening Discourses' at the Royal Institution to achieve this end, and those invited to lecture took the task very seriously and saw it as an honour and obligation.

The process had begun, surprisingly enough, with a woman, Mary Somerville,[26] writing books in the 1820s and 1830s which were very well-received by men of science like Whewell and Faraday. Later, William Crookes, the last non-graduate President of the Royal Society (during the First World War) launched a *Quarterly Journal of Science* (in 1864) which he hoped would catch on as the great literary reviews (the *Edinburgh*, the *Quarterly*, the *Westminster*, the *North British* and others) had done. These published essentially essay-reviews, more or less tightly focused upon one or more recent publications; and served to keep nineteenth-century readers up-to-date on a wide range of topics, including some science. Crookes' *Quarterly Journal* was to be distinctive in dealing with the whole gamut of the sciences only. In the event, by 1864 the era of the great quarterlies was coming to an end, and more frequent publication was becoming fashionable: the journal eventually went monthly, but ran only until 1885. Much more successful was Crookes' *Chemical News*, in magazine format and coming out weekly: much more lively than the publications of the Chemical Society of London, informal, often (like *The Lancet* then, in the medical world) critical of the scientific powers-that-be, publishing much speculative and unconfirmed material, and representing a chemical community now containing many 'professionals', living by their science in industry or in government, and remote from the learned world of academic research.

Chemical News was the model for Norman Lockyer's journal *Nature*, published from 1869 by Macmillan, and for many years in the red, supported as a loss-leader. It cast a glow over Macmillan's textbooks and other scientific works, making the publisher a leader in this field, booming with educational expansion. *Nature* was a vehicle for announcements and preliminary papers, often in the form of letters to the editor; and also functioned through reviews to make specialised scientists aware of what was going on elsewhere. It became essential. Like Crookes, Lockyer was an entrepreneur, a self-made man, a civil servant passionate about astronomy and prepared to speculate, about helium, which he identified in the Sun long before it was isolated upon Earth, and about the life history of stars. Both men were good communicators, and made themselves among the best-known scientists of the years around 1900: busy men, they did much of their research by directing assistants. They filled the gap between elite and popular science, and were prepared to delight in argument, public excitement and controversy.

Elsewhere, magazines like *The Cornhill* and *The Nineteenth Century* had brought a liveliness not always visible in the austere pages of the *Reviews*; and *The Nineteenth Century* particularly, whose editor James Knowles was a friend of Huxley and his X-club associates,[27] carried a good deal of science, especially when it could be made controversial: Huxley's exchanges with W.E. Gladstone over evolution and the Bible are an example; and Huxley died in 1895 in the midst of writing an essay engaging with Balfour's view that science, like religion, rested upon belief.[28] These intellectual encounters with two Prime Ministers tells us something about both science and politics at the time. Huxley was a great stylist, whose writings can still be read with pleasure. He had had to learn to write attractively to support himself when, after returning from a survey voyage in Australian waters, he was elected FRS but was unable for some years to find a job. Scientific journalism filled the gap.

Few scientists by 1900 had the common touch of Huxley, Crookes and Lockyer, all in their way plebeians; and Lavoisier's hopes for an austere language of science, where metaphor would be excluded, was to a great extent realised. The passive voice, the long words, and the compressed style required by editors publishing for expert readers made science hard to read. A career in scientific popularisation had opened up, and interpreters of science found their niche. There was also science fiction: *Frankenstein* had been an early example, drawing upon Davy; and then the novels of Jules Verne; and by the end of the century H.G. Wells' *Time Machine*. Wells had briefly been a pupil of Huxley's, and his book explored the themes of evolution and degeneration: like *Frankenstein*'s, his message was not quite what optimistic and progressive boosters of science would have wished.

Similarly, while cheap books and then newspapers had helped popularise mainstream science, they had also brought before the public a series of scientific heretics. 'Scriptural Geologists' interpreted *Genesis* literally, to the horror of liberal Christians and professional geologists; vaccination, welcomed by most as abolishing smallpox and holding out the promise of similar developments with other infections, was violently attacked by some in the nineteenth century, just as the MMR vaccine was in the twentieth; and vivisection, claimed by physiologists to be necessary for medical progress, was furiously denounced, and in the event restricted and controlled by Act of Parliament. Industrial pollution and the adulteration of food aroused similar outcries, and were eventually controlled (creating jobs for analysts). Scientists were also beginning to play the role of sages, or high priests in what Huxley called the Church Scientific, controlling science: churches and nationalised industries seem to be run for the benefit of their officials and employees, and some had the same unworthy suspicion about the scientific community and its establishment. All publicity, we are told in the world of theatre, is good publicity; and maybe in science that will also apply, but scientists like to be loved.

Nevertheless, it was not clear what was and was not science. Phrenologists aroused much attention with lectures, publications and labelled china heads, connecting the shape of skulls with the development of brain, and hence of personality.[29] In 1850 William Gregory, Professor of Chemistry at Edinburgh, who had translated important books by Justus von Liebig, published Karl von Reichenbach's *Researches*, covering magnetism, electricity, heat light, crystals, chemical affinity and the vital force.[30] A chemical engineer by training, Reichenbach had come to perceive magnetic auras around people, which he attributed to a previously unidentified force called odyle, or od for short. Even in the 1920s, this idea, presented as an insight like others in history unappreciated by blinkered experts, was still worth re-publishing by a London publisher.[31] Meanwhile there had been the great excitement caused by the coming of spiritualism, and its seances. In this case, the Society for Psychical Research, including eminent scientists, was founded to investigate the curious phenomena observed in the presence of respectable witnesses.[32] They had been literally in the dark; and those trying to investigate and explain found themselves metaphorically there. But telepathy, disappointing though it was in its failure to be dependable and reproducible, was studied, and the unconscious postulated. Science for the public was not straightforward, and the favourites of some publics were disapproved of by leading scientists – though other unrespectable ideas, like evolution, which had been less well-thought-of than phrenology, came triumphantly through expert hostility to flourish in our time.

The nineteenth century was an age of empires and colonies, the settling of Australasia and the American West, the consolidation of British India and French Algeria, and the scramble for Africa. All this generated and required science.[33] In 1800 much of the globe was still blank. 'Darkest Africa' became proverbial, but the interior really was unknown then to Europeans. James Cook had made it clear that there was no great unknown temperate southern continent, but whether New South Wales and New Holland formed one land mass or were a collection of islands was unclear, and the interior of what Cook's successor, Matthew Flinders, was to call Australia was also unknown. Central Asia was a mystery. South and Central America too were little explored, and while Alexander Mackenzie had reached the Pacific in Canada,[34] nobody had yet crossed the Rocky Mountains in what became the USA; California was still Spanish. When, as a student in 1959, I went to Madagascar, there were still blank spaces on the map, great tracts of forest without air or ground survey; but really by 1900 there were very few areas quite unknown to geographers. The world had been explored. This was partly due to government-sponsored expeditions, 'big science', like Cook's, from Britain, France, the USA and Russia in particular; and partly to much smaller and cheaper journeys by individuals or small groups, like Mackenzie's had been. Sailing ships, with all the skills involved and the problems they presented on lee shores, in calms, and contrary winds, had given way to speedy steamships.

For Joseph Banks, his voyage round the world with Cook had been the high point of his life, and during his almost forty-two years as President of the Royal Society he loved to reminisce about it. Subsequent Presidents served briefer terms, and included Edward Sabine, Huxley and Joseph Hooker who had, like Banks, learned much of their science on their travels. Banks' journal was not published in his lifetime,[35] but many eminent scientific travellers[36] wrote up their reports in a readable way, giving rise to classics like Alexander von Humboldt's on South America, Meriwether Lewis and William Clark's on their journey across the USA, John Franklin's on arctic Canada, Darwin's on his voyage around the world, Henry Walter Bates' on the Amazon, David Livingstone's on central Africa, Alfred Russel Wallace's on the Amazon and on Indonesia, and Thomas Belt's on Nicaragua. The public appetite for scientific travel was huge, and the Royal Geographical Society, the US Congress which commissioned and published the *Pacific Railroad Reports*, and other bodies helped to feed it. Many such writings were not merely accurate descriptions of territory previously unknown to westerners, but also got across new scientific ideas.

Thus Humboldt showed that it was possible to map more than topography, starting physical geography with his isotherms and isobars; and also indicated visually how increasing altitude affects climate, so that mountain tops in Equador are like Spitzbergen. Darwin puzzled over the fossils of Argentina, and the fauna of the

Galapagos Islands. Franklin's instruments, and those of Sabine, had to be modified to suit the extreme conditions. Bates noticed and described how butterflies from genera tasty to birds had evolved to look like distasteful species by natural selection, thus providing early examples of Darwinism in action.

Wallace in Indonesia not only independently hit upon the idea of natural selection, stimulating Darwin to publish in *The Origin of Species* (1859)[37] the mass of evidence he had been collecting over the years, but also saw how the animals and plants of different regions have different characteristics. Thus Bali and Lombok are separated by a narrow but very deep strait: Bali's fauna and flora are basically Asian, Lombok's Australian. Some travellers were like tourists on a cruise, based upon their ship and carrying a little bit of Europe and its assumptions with them. Wallace, living for long times among communities on the Amazon and in Malaysia, was (like Livingstone and some other scientific travellers) free of the casual racism so characteristic of the nineteenth century; his readers would have been challenged about their prejudices in regard to natives and savages, whom he did not regard as left far behind in an evolutionary struggle for existence. Readers of travel books could pick up important scientific ideas while following a ripping yarn of adventure and derring-do. John Herschel edited for the Admiralty a *Manual of Scientific Enquiry* (1849)[38] with advice from travellers (including Charles Darwin) on what to look for.

Stay-at-homes could also see some splendid pictures of exotic places. Illustration, based upon copperplates engraved or perhaps etched, had been very expensive before 1800, but the coming of wood engraving and then of lithography had made the printing of illustrations and maps much cheaper. Works of travel and natural history, and descriptions of experiments in chemistry and physics, were made much more attractive by a proliferation of illustration. But here, as with language, in works of science the pictures gradually came to look more like diagrams. The point was to get across things of scientific importance; and there was a tension between beauty and usefulness which was hard to resolve. The development of photography, a scientific art, downgraded topographical pictures; but for living creatures, where for scientific purposes a picture of a species of parrot rather than a portrait of Polly is required, an artist has continued to have an important place. We all enjoy good pictures, and they can be an important part of public understanding of, and relish for, science.

Science fiction was one kind of novel based upon science, but an interesting genre in the nineteenth century was the novel of religious doubt. Doubt was sometimes caused by scientific discoveries, though much more often and seriously (even probably in Darwin's own case) by bereavement, resentment at clerical pretensions, or unease generated by Biblical criticism. But the autobiographical novel by J.A. Froude, later a distinguished historian, *The Nemesis of Faith* (1848), caused a tremendous sensation; as later did Mary (Mrs Humphry) Ward's *Robert Elsmere* (1888), which was reviewed by Gladstone, and even given away in a soap promotion in the USA. Paley's *Natural Theology* was published towards the end of his life, in 1802. It was a great publishing success, with updated editions coming out regularly over half a century.[39] While it was not universally welcome, its utilitarian philosophy was more disliked than its general argument for Design, which was generally accepted.

The world closely examined seemed more and more to disclose the wisdom of God, which was also a title given to Jesus.[40] True natural theology should therefore show the harmony between natural and revealed religion, thus making science momentous and accessible to all in a religious age. Most popular science in the first half of the century was indeed permeated by natural theology, though the First Cause lying behind the law-governed world revealed by science might often seem very different from the Judeo-Christian loving Father. By 1900, popular science had become much more secular: agnosticism had become respectable, and people were even prepared to describe themselves as atheists, previously a term of abuse. For the first time, it was common to see religion and science in conflict. It is to natural theology and its decline that we now turn.

balls, but active centres of force, repulsive at short distances (to account for elasticity) and attractive at greater ones (to account for gravity). Priestley's interests in electricity and in gases thus complemented his religious beliefs. He had a stammer, a serious defect in a preacher; but he wrote beautifully and clearly and was a powerful advocate for Unitarianism, science and political liberty – notably full rights for dissenters.

His support for the French Revolution of 1789, as earlier for the Americans, was strident, and in the last 'Church and King' riots so far in Britain, his house in Birmingham was sacked by a mob on Bastille Day, 14 July 1791. He fled, but found himself unwelcome in London, where Banks,[5] as President of the Royal Society, was doing his best to demonstrate that real science was not subversive[6] (as it seemed to have proved to be in France); and therefore emigrated reluctantly to the USA, ending his life under the Presidency of his friend Thomas Jefferson. Outside the Unitarian Church, in the political reaction and war beginning in the 1790s, Priestley's synthesis of religious belief and science did not catch on. For Banks and his associates in the elite scientific community based in London, science must go with respectable religion and due deference to the British constitution. Active, even thinking, matter would not do: another metaphor was needed.

Every bit as alarming was the dynamical idea that God had allowed the world to change and evolve without further interventions on His part. Jean Jacques Rousseau believed that savages were nobler than the calculating and double-dealing men and women in more civilised communities. If that were so, then orang-utans (and the very term in Malay means 'wild man of the woods') must be nobler still. The Scottish judge Lord Monboddo thought so; and Percy Bysshe Shelley's friend Thomas Love Peacock wrote a novel, *Melincourt*, in which the hero is an ape who becomes Sir Oran Haut-Ton, is very much the natural gentleman, though of superhuman strength, and is eventually bought a seat in Parliament – where his being able to vote but not speak makes him particularly valuable. Charles Linnaeus, the great Swedish classifier, had put the orang-utan in our genus (calling him *Homo sylvestris*) much nearer to us than apes are put today. Speculations about primitive peoples in remote places who still had tails were popular, as the youthful Thomas de Quincey tells us.[7] But it was in the writings of Erasmus Darwin that the notion of the evolution of mankind and of society was presented to a wide audience and became a part of popular science.[8]

Darwin was a very successful provincial doctor, who with Priestley, Josiah Wedgwood, James Watt and other men of science and manufacturers belonged to the Lunar Society of Birmingham. Meeting at the full moon, so that they would have light to get home afterwards, they discussed all kinds of scientific topics informally and without deference to religious authority.[9] Darwin took to poetry in *The Loves of the Plants,* popularising Linnaeus' botanical system in which the classification of flowers depended upon counting their sexual parts. Thus the Pentandria Digynia, which includes the gentians, has five male and two female organs in each flower – in bed together. In Darwin's robust eighteenth century, this could be the basis of a good deal of joking; and his poetry exploited these possibilities, and at the same time made the new botany familiar to a wide readership. Its lightness, optimism, vivid imagery, Deism and curious science made it attractive to both men and women. Indeed, by the 1790s, Erasmus Darwin was one of the most popular and widely read poets writing in English.[10]

The Loves of the Plants formed part of what became a bigger work, *The Botanic Garden* (1791) where the poetry was accompanied by an astonishing series of footnotes and endnotes, packed with curious information. For us, poetry that needs footnotes would be a turn-off; but didactic verse was clearly a genre popular with our ancestors. At the end of the century, the new poetic voices of William Wordsworth and S.T. Coleridge in *Lyrical Ballads*[11] (1798) created a furore and a new fashion. In 1803 Darwin's last poetic book, *The Temple of Nature, or the Origin of Society,* was published, a year after his death. By then Darwin's seemed one of the last voices of the Enlightenment, outdated, surviving into the epoch of the French wars, Romanticism and the evangelical revival spurred on by Wesley. Darwin proposed a progressively evolving world, and his text and notes are full of curious observations and arresting conclusions. There are even anticipations of natural selection in the struggle for existence: facing up to 'And one great Slaughter-house the warring world!', where even 'vegetable war' goes on endlessly as plants compete for soil and light. And yet things are improving and going upward. Darwin and his circle had little time for orthodox religion – the Wedgwoods[12] called their Unitarianism 'a featherbed to catch a falling Christian' – and there is no role for God to play as the world unfolds in conformity to the powers inherent in matter. With a war on, and a new intellectual climate, this would not do; and Darwin's poetry and broad sweep were mocked.

Robert Boyle in the mid-seventeenth century had been much impressed by the great clock at Strasbourg, which (after a number of rebuilds) still marks noon, local time, most strikingly with chimes, doors opening and shutting, and figures processing. To see why something happened it would be necessary to look inside and trace the mechanism. For Boyle and his contemporaries, the world was a great clock, and science a matter of finding its mechanisms.[13] This view gradually became popular, in what we call the Enlightenment,[14] at any rate among intellectuals. Taking something to bits and putting it together again, analysis and synthesis, became the ideal in chemistry and physics, even if not fully practicable in zoology.

Clocks are driven by a mainspring or a weight, and while it might be alright to see God as the mainspring of the world, in terms of terrestrial politics such a view went with despotism. William Harvey's comparison of the King to the heart probably delighted his autocratic patron Charles I; and Louis XIV might see himself as the driving force behind a kingdom running like clockwork. But, in Britain and America, by 1776 a rhetoric of checks and balances came to replace the more complex imagery of clockwork in political discussion. This was however just the time when the chronometer had been perfected for the discovery of longitude. Local time was compared with that shown by the chronometer set on the meridian at Greenwich, and the difference gave the longitude – one hour corresponding to 15°. The success of John Harrison, and then other makers, in fashioning clocks which kept good time in a pitching and tossing ship, voyaging for weeks or months through extremes of temperature, caught the public imagination and made the mapping of Cook and his successors very much easier.[15]

Clockwork thus became fashionable again in time for William Paley to write his celebrated *Natural Theology*, first published in 1802.[16] This book was the culmination of a life devoted to writings defending Anglican Christianity. He imagined finding a watch on the path, picking it up and noting how well all the parts work together. There is glass so that we can see the hands; when we open the case, we see intricate brass and steel work, nothing redundant and ingenuity everywhere. How absurd it would be to say that atoms had come together by chance to generate a watch. There could be no doubt that it had been made; it displayed design and craftsmanship. The rest of the book is a series of arguments, cumulative rather than rigorous, to show that the world is an enormous clock, and that the animals and we are little watches; and that God has chosen to make the world the happiest possible. We enjoy eating, for example, which might be merely tedious refuelling; and even the shrimps seemed to Paley to enjoy their swim in the then-unpolluted waters off the coast of Cumbria. From all the examples of contrivances that Paley gives, his readers would absorb a good deal of the biology, anatomy and physiology of the day.

They would also have learned some non-mathematical astronomy, for Isaac Newton had demonstrated the power and wisdom of God that lay behind the planetary orbits and the simple laws to which they were subject. Paley was, like Newton, a Cambridge man, and his well-written and accessible books on moral and political philosophy and evidences for Christianity became required reading there. William Pitt, the Prime Minister, admiring his *Moral Philosophy*, called him 'the best writer in the English language';[17] Charles Darwin found *Evidences* and *Natural Theology* the only useful and congenial part of his formal courses in Cambridge. At the new University of Durham, founded in 1832, the same rule applied. Some editions of *Natural Theology* have questions at the back to help students swotting for examinations. Paley, who had a career in the Anglican Church taking him from Cambridge to Carlisle, and ending up with posts in the industrial city of Sunderland and in Lincoln, was careful to note that natural religion based upon science could only be a preparation for revealed religion, in the Bible, and not a substitute for it. In France Robespierre had sought to replace the feasts of the Church with a Festival of the Supreme Being; that is, to establish natural religion. Paley would have none of that.

A problem was the evil and pain in the world, for Paley could not fail to describe the contrivances by which animals snare and eat each other. His solution was to adopt utilitarianism from the otherwise heretical Priestley, who had popularised the phrase 'the greatest happiness of the greatest number'. On balance, the world was one in which God had maximised pleasure and minimised pain, as we should seek to do in our moral lives. Carnivores were for Paley machines for euthanasia: the antelope in late middle age was spared the pains of arthritis and decay by being gobbled up by the wolf – it was all over quite quickly – and the wolf had the pleasure of a good dinner. A world with carnivores was therefore happier than one without. Ichneuman flies, whose larvae slowly devour living caterpillars within which they live, and gadflies which lay their eggs beneath the skin of cattle, were a little more of a problem (they darkened Darwin's poem); but nobody could deny the ingenuity of the Creator, even if He moved in mysterious ways. As consolation to the invalid, the widow or the orphan whose parents were eaten by wolves, the message that on balance the world is the happiest possible is never very effective; but Paley, like Priestley, wrote very well, and with real enthusiasm. Generations of students and other readers absorbed much science from him; and the message conveyed was reassuringly that of Francis Bacon, that real science rightly understood must support true faith and sound political institutions.

War between France and Britain broke out in 1793, and lasted with only a brief half-time break in 1802 (the Peace of Amiens) and another in 1814 until the battle of Waterloo in 1815. A whole generation grew up who had known nothing but world war, for there were battles in the West Indies, the USA, Egypt and India as well as in Europe, from Portugal to Moscow, and Britain took over the Dutch colonies in Indonesia and at the Cape of Good Hope. Napoleon, who seized power in November 1799, brought the Pope to France where he was kept under what was in effect house arrest at Fontainbleau. Napoleon signed a Concordat, restoring Roman Catholic worship in France; but to outsiders, his Empire looked as ruthless and irreligious as the revolutionary governments had been. Science, in the writings of Denis Diderot, Jean d'Alembert, Voltaire and Rousseau, seemed to have been the corrosive agent that had undermined the ancien regime; and in revolutionary and Napoleonic France, it duly flourished mightily.

Indeed, Paris was the world's centre of excellence in science right through the years of upset and war. Science there could be communicated as modern and republican. In mathematics, astronomy, experimental physics, chemistry, medical sciences, zoology and botany, the French were the leaders. The Academy of Sciences was closed, and the great chemist and fat-cat taxman, Antoine Lavoisier, executed in 1794, under the Terror; but scientific organization was soon revived in the First Class of the new Institut.[18] Men of science rallied to the republic, supervising the melting of church bells into cannon and other preparations for total war; while Napoleon fancied himself as a scientific man, and was duly elected to the Institut. There were bright individuals in Britain and Germany, but outside medicine there were few paid posts in science and nothing in the educational system to match the new and meritocratic École Polytechnique which combined teaching with research, and trained engineers and men of science.

It was the new industrial economy of Britain (in places like Birmingham and Sunderland) that defeated the French; for, while France led in science, Britain had the new technology of steam engines and textile machinery, based on organised common sense rather than recondite research or the latest theory. Dissenters were prominent in industry, and in banking: capitalism was underway. Bacon had believed that science would enable mankind to evade the curse put upon Adam and Eve when they were expelled from Eden: it would reduce labour, pain and disease, and make the world fruitful. Science as a useful activity that would improve standards of living had therefore a religious aspect in Regency Britain.

While Davy was dictating his dialogues to the bored medical student, John Tobin, who was his companion in these last travels,[22] the Earl of Bridgewater died in February 1829. He had been heir to a canal fortune, and he bequeathed the large sum of £8,000 in trust to the President of the Royal Society to nominate authors to write books on the power, wisdom and goodness of God as manifested in the Creation. Davies Gilbert (formerly Giddy), the Cornish MP and mathematician who had succeeded Davy, discussed the bequest with the Archbishop of Canterbury and the Bishop of London. They settled upon finding eight authors, who would each take a different branch of science. This was to be a more orthodox exercise than Davy's *Consolations*; most of the authors were Anglicans, but Thomas Chalmers was a Presbyterian and a leading light in the Church of Scotland, and later in the Free Church. He had established a great reputation with lectures on the Newtonian universe, and God's wisdom and goodness displayed therein, in Glasgow. His *Treatise* was concerned with the adaptation of external nature to our moral and intellectual constitution. John Kidd, Professor of Medicine at Oxford, wrote about our physical condition; William Whewell of Cambridge about astronomy; Charles Bell, from Edinburgh, on the human hand; Peter Mark Roget (now famous for his *Thesaurus*) on physiology; William Buckland on geology; William Kirby on habits and instincts, notably of invertebrates; and William Prout on chemistry, meteorology and digestion – a rag-bag of sciences left over, where he had interesting things to say about the atoms of matter. The volumes came out over several years, as their authors finished them, and thus not exactly in order; and they proved (surprisingly to publishers who had turned the project down[23]) to be a publishing success story, selling very well for many years, first in expensive editions, and then in cheaper reprints.

The whole series, appearing between 1833 and 1836 and written by prominent members of the scientific establishment, demonstrated the continuing power of natural theology as a splendid vehicle for popular science at a time when, in Oxford (and to a smaller extent in Cambridge), there was a great revival of religion in a form largely indifferent to science. The Reform Bill of 1832, which extended the vote to the middle classes, was the culmination of a process that had in the 1820s brought full civil rights to Protestant dissenters and then to Roman Catholics. It seemed to John Keble, poet and Anglican clergyman, that this represented national apostasy: and he said so in an Assize Sermon preached before the judges in Oxford in 1833. He was soon joined by E.B. Pusey and John Henry Newman in a campaign to restore the fortunes of the Church of England, and to emphasise in his book, and also in Cambridge where he became a great man (Professor of Mineralogy, and then of Moral Theology, and finally Master of Trinity College) and upheld the position of applied (or 'mixed') mathematics, with its empirical connections, in the syllabus.

Geology, with its vistas of deep time,[27] also attracted the attention, and sometimes raised the hackles, of the religious-minded in a way that chemistry, mineralogy and digestion probably did not. Buckland, like Whewell, was an ordained clergyman of the Church of England.[28] This was the usual step for anybody following an academic career, or one in the newly developing Public Schools; it brought moral and intellectual authority, but entailed defending church doctrine. Buckland had in his *Reliquiae Diluvianae* (1823) inferred from the bones of hyenas found in a cave in Yorkshire that the cave had been their den, and that they had been drowned in Noah's Flood. They were a different species from modern African hyenas, but very similar; and in particular, they crunched the bones of their prey in just the same way, and their whitish faeces were alike – Buckland carefully observed hyenas in a menagerie. Cuvier had reconstructed extinct creatures from fossil bones found in the quarries of Montmartre when Napoleon was rebuilding Paris in Imperial splendour, and had concluded that there had been a succession of faunas and floras in France, separated by catastrophes. To Buckland, the first geologist awarded the Copley Medal of the Royal Society (its highest honour) for his work, the Flood was the latest of such cataclysms. The medal was presented by Davy, who remarked that this was the first time in its ninety-year history that it had gone to a geologist: the science was prestigious and popular, and its connections with *Genesis* made it exciting for everybody.

Nobody at Oxford then could study for a degree in geology (or indeed anything except for Classics and Philosophy – 'Greats' – or in some cases Mathematics), but Buckland and other Professors gave lectures to which anybody interested could come. Among those who did was Charles Lyell, intended for the law but seduced by geology. He believed that his professor (and Cuvier) had been misled into perceiving series of catastrophes because they had not allowed long enough for the ordinary processes of uplift, deposition and erosion to do their work: they were prodigal of violence because parsimonious of time. Lyell's *Principles of Geology*, beautifully argued with a lawyer's skill in presenting a case, appeared in 1830–3 and proposed that past changes should be explained exclusively in terms of processes now operating.[29] This meant a history of hundreds of millions of years, in apparent

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