INTRODUCTION

What is an Experiment? What is Beauty?

Some experiments, it must be said, are best left alone. ‘I was desirous’, Francis Bacon wrote from his sickbed in 1626, ‘to try an experiment or two touching the conservation and induration of bodies; as for the experiment it succeeded excellently well.’ An ailing old man of sixty-five, Bacon bought a chicken from a woman in Highgate, a village near London, and filled it full of snow during one of the fierce winters of what we now call the Little Ice Age. This exercise in refrigeration may have worked well enough, but Bacon caught a severe chill and was taken to bed at the house of the Earl of Arundel, where his condition developed into pneumonia. He died within a month.

The irony is that this was one of the few experiments that Bacon, often designated the father of experimental science, actually performed himself. Yet he was a tireless advocate of the experimental method as a way of procuring sound scientific knowledge. ‘Our hope of further progress in the sciences’, he wrote in his greatest treatise on scientific method, the *Novum Organum*,

> will then only be well founded, when numerous experiments shall be received and collected into natural history, which, though of no use in themselves, assist materially in the discovery of causes and axioms; which experiments we have termed enlightening, to distinguish them from those which are profitable. They possess this wonderful property and nature, that they never deceive or fail you; for being used only to discover the natural cause of some object, whatever be the result, they equally satisfy your aim by deciding the question.

This sounds very much like the traditional formulation of the scientist as someone who devises an experiment to discover something about how the world works, from which more general laws of nature may be deduced. And that is indeed a fair description of the project Bacon envisaged. He rightly complained that, previously, science had lacked any systematic means of gathering reliable knowledge. Instead, it had been pursued (he implied) in a piecemeal fashion by men who sat around thinking up idle dogma based on uncritical acceptance of every report and rumour they heard, or alternatively who carried out ‘experiments’ with no particular rationale in mind and with little heed to the lessons they might learn. The alchemists, for instance, experimented haphazardly with the sole aim of making gold and getting rich. Thus, said Bacon,

> those who have treated of the sciences have been either empirics or dogmatical. No one has yet been found possessed of sufficient firmness and severity to resolve upon and undertake the task of entirely abolishing common theories and notions, and applying the mind afresh, when thus cleared and levelled, to particular researches; hence our human reasoning is a mere farrago and crude mass made up of a great deal of credulity and accident, and puerile notions it originally contradicted.

And these shortcomings, Bacon felt, existed because no one did decent *experiments*: ‘Nothing is rightly inquired into, or verified, noted, weighed, or measured . . . . We must not only search for, and procure a greater number of experiments, but also introduce a completely different method, order, and progress of continuing and promoting experience.’

This method was what Bacon aimed to set out in his *Novum Organum* or ‘New Organon’. The Greek word *organon* means an instrument or engine: Bacon’s new engine was the device that would churn out a new philosophical understanding of the world, and it is characteristic of Bacon that he should choose a metaphor from applied science to describe his project. The *Novum Organum* was published in 1620 as a part of a still greater enterprise, *The Great Instauration*, which Bacon intended to be a more or less encyclopaedic account of science as it was then known, coupled with his dream of a new scientific method and a description of the fruits that this approach had already yielded. All Bacon managed to produce of the six volumes intended for his magnus opus, before he was laid low by a frozen chicken, was the introductory material (also published in 1620 under the umbrella title *The Great Instauration*), the second part (which constituted the *Novum Organum*), and a mere sketch of the third volume, *A Preparative Towards a Natural and Experimental History*.

Yet Bacon's vision of an institutional body dedicated to the systematic pursuit of scientific knowledge provided the template for the Royal Society, granted its charter by Charles II in 1665, which brought together (even if it did not exactly unite) such great scientists of the early Enlightenment as Isaac Newton, Robert Boyle, Robert Hooke and Edmond Halley. It is tempting now to regard Francis Bacon as the progenitor of the modern concept of a scientific experiment, wherein accurate and ingenious instruments and devices are deployed so as to reveal the secret workings of the universe.

While that picture has some validity, it isn't quite what Bacon had in mind. His sights were set on a somewhat different destination – for he did not consider the knowledge garnered from experiments to be the ultimate end in itself. Rather, in his famous formulation, knowledge delivers power. The reason why humankind should seek out scientific knowledge is not simply to *know* it but to *apply* it to achieve mastery over nature. Those who merely wove knowledge into intricate, abstract theories, said Bacon, were like spiders spinning their webs. On the other hand, those who seek worldly profit through blind empirical blundering were like ants which 'only heap up and use their store.' The true scientist, he said, should be like the bee, which 'extracts matter from the flowers of the garden and the field, but works and fashions it by its own efforts'. In Bacon's *New Atlantis* (1627), a vision of a utopian society governed by a cadre of scientist-priests who work in a quasi-mystical research institution called Salomon's House, this knowledge produces some truly wondrous inventions:

> We have some degrees of flying in the air; we have ships and boats for going under water, and brooking of seas; also swimming girdles and supporters. We have divers curious clocks, and other like motions of return, and some perpetual motions.

All of this starts to sound rather less hard-headed and more fantastic than we might expect from a man who is ostensibly banishing old superstitions and drawing up a blueprint for a new and reliable scientific method. But that is not surprising; for as science historian John Henry has argued, Francis Bacon's vision of an experimental science drew not so much on the model we would now associate with scientific Enlightenment rationalism, but on the older tradition of natural magic. Experimental science was born out of this magical legacy – a truth acknowledged in the very title of the definitive, multi-volume survey compiled in the 1940s by American historian Lynn Thorndike, *History of Magic and Experimental Science*.

Until we understand this, we will not truly comprehend the experimental tradition in the sciences – and it will be the harder to see how a book like the present one fits into it. To many scientists, a 'beautiful experiment' is one that is perfectly and elegantly designed to yield an insight about the way the world works. That is indeed one kind of experiment, and we can certainly find some beautiful examples of it. But for Bacon, the notion of 'experiment' never lost touch with its roots in the concept of 'art' or *techne*, the Greek word from which 'technology' is derived. It was about making things; and that had, ever since ancient times, the taint of wizardry about it.

During the Renaissance, 'experiment' was sometimes regarded as a dirty word by the Roman Church. According to Pedro Garcia, the bishop of Ussellus in Sardinia, experiments were a form of diabolical magic and should be suppressed:

> To assert that such experimental knowledge is science or a part of natural science is ridiculous, wherefore such magicians are called experimenters rather than scientists. Besides magic, according to those of that opinion, is practical knowledge, whereas natural science in itself and all its parts is purely speculative knowledge.

This was not just because those who dabbled in experiments were liable to be alchemists, astrologers and other heretics who sought to understand and control the occult, demonic forces of nature. It was also because to conduct an experiment was to perpetrate the abominable impiety of asking God a direct question, and perhaps even of coercing him to give an answer. For the thirteenth-century French philosopher William of Auvergne, experimental magic was a 'passion for knowing unnecessary things'. It was in such an intellectual climate that the 'curiosity' that motivated experiments became considered a sin, a 'lust of the eyes' in St Augustine's words.

That is precisely why true science could not even exist without experimentation. The Classical Greek philosophers such as Aristotle and Plato were scientists to the extent that they believed things happened because of natural mechanisms, not through the whimsy of the gods; and they were determined to root out these causes using reason and logic. But on the whole, theirs was the logic of abstract thought, which can never get you very far – because our intuitions about nature are seldom reliable. (You need only read Plato's recommendations for making colours by mixing to realise that he probably never picked up a paint brush.) It wasn't until Greek thought mingled with Middle Eastern artistry in the crucible of polyglot Alexandria that proto-scientists came to appreciate the value of experiment. This philosophical melting pot of Hellenistic Greece produced some of the finest ancient experimentalists, such as Hero and Archimedes.

We have to be careful, however, what we understand by 'experiment' here. Today scientists use a well-designed experiment to probe and perhaps to falsify a theory, or to enable them to choose between different theoretical interpretations. Yet, until the Renaissance, it was extremely rare that an experiment would be conducted to *test* an idea: it was simply a way of demonstrating that you were right.

Even so, there was a difference between actually doing the experiment and just talking about it. The Arabic alchemists of the ninth and tenth centuries appreciated that experimental science must inevitably be a quantitative science. In contrast to the qualitative theories of Aristotle, they gathered knowledge by weighing and measuring, using sophisticated instrumentation: balances, rulers and so on. Experiment creates a demand for instruments, but by the same token, instruments make new experiments inevitable.

So the fact is that, for the Whiggish historian of science (and many practising scientists fall into this category), experiment has roots every bit as disreputable as Garcia implies. Experimental science was not a part of the natural philosophy studied in the medieval and Renaissance universities; it was something done by alchemists and magicians, by the mystical adepts of the Neoplatonic tradition. Medical doctors studied anatomy from books, and the cutting up of bodies was left to unlettered surgeons (which was why the mistakes of the Classical writers persisted for so long). Useful materials like dyes, alkalis and soap were manufactured by artisans and tradesmen. Scholars who, like the thirteenth-century Franciscan monk Roger Bacon, showed an appetite for experiment were inevitably labelled as wizards.

Roger's namesake Francis, nearly four centuries later, professed contempt for alchemists, magicians and their ilk. They had, he said in the *Novum Organum*, so far exerted 'faint efforts' that had met with 'meagre success.' But that was not because natural magic itself was a pile of nonsense; rather, it was because its proponents were hitherto mostly fools and charlatans. Henry points out that Bacon, like most of his contemporaries, 'willingly accepted [that] astrology, natural magic and alchemy were noble and worthwhile pursuits even though, in practice, they were full of error and futility'.

Well, so what? Why should it matter that the 'father of experimental science' drew inspiration from an occult tradition that today plays no role in science? Why should we care that the very concept of a scientific experiment has roots in magic and practical 'arts'?

I believe that bearing this in mind should help prevent us from being too narrow-minded about what we imagine an 'experiment' is. To define it as an enquiry into nature would be to impose a modern definition that denies a great deal of the genealogy of experimental science. I would argue that, at all times before the twentieth century, experimentation was closely linked to *techne*, to applied science and to the skills of the fabricator and the artisan. This perspective, moreover, is particularly important within the context of chemical science, because that discipline has a history that is in many ways quite distinct from the history of physics or biology (with their origins in natural history and the observation of nature). Some areas of what we would now deem to be the sciences of the material world, such as metallurgy, have only rather recently established firm connections with the 'fundamental' sciences on which we now consider them to be based. Likewise, there has been a convergence between some strands of applied chemistry – the manufacture of dyes and pigments, and of soaps and detergents, and the brewing of beverages – with 'academic' science only since the nineteenth century, and that was itself largely driven by the demands of industry for more reliable and versatile methods of synthesis, rather than because academia decided for itself that these 'arts' were worthy of intellectual effort.

This is perhaps why chemistry is so conspicuously absent from some recent books both about the history of science and about its future prospects: it does not 'fit' today's modish model of what science is. The truly bizarre result is that we now have an image of 'science' that is largely at odds with the way it is actually practised. Philosopher of science Joachim Schummer has estimated that there are more – many more – scientific papers published in chemistry than in any other scientific discipline. 'Thus', he says,

> if we want to know what our actual sciences are about, we should – from a quantitative point of view – first and foremost turn our attention to chemistry. Or, to put it in different terms, philosophies of the natural sciences that neglect chemistry should arouse our strongest suspicion.

What's more, the overwhelming majority of those papers report the results of experiments. 'Chemistry', says Schummer, 'has always been the laboratory science *per se*,'

> such that still in the 19th century the term 'laboratory' denoted a place for experimental research in which *chemical* operations were performed. The chemical laboratory became the model for all the other laboratory sciences when they replaced 'thought experiments' by real experiments. Although chemistry is no longer the only experimental science, it is by far the biggest one and historically the model for all others. Thus, if we want to know what scientists mean by 'experiment', chemical papers are the right point to start with.

Schummer points out that roughly a third of all scientists worldwide are engaged not in the experimental testing of theories, but in producing (and characterizing) new substances – in chemical synthesis. Chemistry, as the eminent French chemist Marcelin Berthelot recognized, creates its own object: it is not necessarily an inquiry into nature, but sets synthetic goals that are shaped by the considerations of the engineer, in particular by the issues of function and design. Synthetic chemistry has its own aesthetic: the 'unnatural' molecules that chemists try to make, while bounded by practical issues such as stability and synthetic accessibility, are ultimately no less a 'designed' product than motor vehicles or buildings, and as such their structure is not inevitable. This brings an added dimension to the notion of a 'beautiful' experiment in chemistry: the beauty need not lie in the conception or the execution, but in the product.

Thus, it seems to me that any attempt to discuss 'beautiful experiments', not just in chemistry but in the whole of science, becomes a skewed endeavour if it neglects that aspect of experimental science engaged in *techne*, in a tradition allied to the arts and crafts, a tradition of making useful and marvellous things – the tradition, indeed, that Francis Bacon drew upon in setting out his ground-breaking plan for giving science a logical and organized structure.

And just what is beautiful?

Good question. Happily, the places and people and things that we find beautiful are many and varied – which means that the selection of experimental examples in this book can never be more than arbitrary. I was heartened by the fact that after I had drawn up a shortlist for the challenge set by the Royal Society of Chemistry – to identify the ten 'most beautiful' experiments in chemistry – I discovered that the American Chemical Society (ACS) had already conducted the same exercise a year previously, and had come to many of the same conclusions as mine. In late 2002 the ACS canvassed its members to submit proposals for the list, and the shortlist of 25 was then assessed and ranked by a panel of chemists and science historians whose combined authority exposes my own list as the scribblings of a rank amateur. At that point, perhaps, I should have just jettisoned my own efforts and adopted the ACS 'top ten'.

But of course, there were parts of that list with which I didn't agree at all. While encouraged by the coincidences with my own choices, I was also stimulated to defend the differences. I ended up striking off my list one experiment that in fact appeared high in the ACS's top ten. Only in one case was I led, after much reflection, to include an experiment I'd originally neglected.

What struck me most about the ACS list, however, was first how it seemed to conflate 'experiment' with 'discovery' – the now pervasive paradigm for historical and philosophical discussions of scientific work. And, second, I noticed how 'beautiful' was often equated by the panellists with what one of them called 'conceptual simplicity', coupled to the lingering notion that a 'beautiful' experiment ought also to be an important one. Indeed, the editorial article accompanying the list defined beautiful in this instance as 'elegantly simple but significant.'

Elegance and simplicity are surely among the key attributes that entitle an experiment to be labelled beautiful, and some of my selections have been made for that reason. But it is not at all clear that these should be the only, or even the principal, criteria for every selection. In fact, if there was ever any intention of that being so for the ACS list, it was flouted more than once. For example, William Perkin's synthesis of aniline mauve, the first aniline dye, in 1856, which fetched in at number 5 in the final ranking, was as messy and inelegant an experiment as one could imagine: the dye was the initially unpromising residue produced by a wholly misconceived attempt at chemical synthesis (see page 154). But the colour itself was surely beautiful, and to my mind that counts for something – albeit not enough to win a place on my list.

As for the issue of significance: there is no real reason why we should demand that a beautiful experiment also be an important one. In practice, that consideration takes care of itself, however, since inevitably the experiments we tend to record and recall and analyse in sufficient detail to know what really happened are those that made an impact. So all of the examples I have chosen do have some broader significance in chemistry or in science more generally. But they are not chosen specifically for that reason, nor are they in any sense meant to represent milestones in the evolution of chemical thought or practice.

I hope I will have said enough by now to justify the position that regards 'experiment' as implying 'experimental science', which could involve a series of investigations, perhaps even spanning several years. This means, however, that compiling a list inevitably means comparing apples and oranges: how do you weigh a single, neat test of some hypothesis against a conclusion derived from the dedicated accumulation of data over a long period? The former can have the beauty of a dramatic revelation; the beauty of the latter can derive from the construction of a coherent chain of logical argument and deduction. For example, experiment number 3 on the ACS list, the determination by the German chemist Emil Fischer in the early 1890s of the precise three-dimensional structure of the glucose molecule, was, in the words of science historian Peter Ramberg,

> part of a large research project involving several smaller projects on the classification of the natural monosaccharides [sugars] that gradually came together in 1891 . . . . There was therefore no one specific experiment that 'determined' the configuration of glucose. This would be an example perhaps of 'beautiful chemical reasoning', rather than a specific experiment.

The same is true of Antoine Lavoisier's work on the oxidation of metals in the seventeenth century, which led him finally to his oxygen theory of combustion. It was a milestone in chemistry (see page 30), it was ranked number 2 in the ACS list – but I am afraid it seemed just too diffuse an endeavour even for me to regard as a single 'experiment'.

Yet I have tried to take a very loose view of how one should regard both ‘beautiful’ and ‘experiment’. One of the key themes in all of the cases I have chosen is that they are shaped by human attributes: invention, elegance, perseverance, imagination, ingenuity. This has tended to work against the inclusion of experiments (like Perkin’s) whose success depended on serendipity: chance discoveries are appealing and entertaining, but I find it hard to see beauty in sheer good fortune. (Admittedly, however, most serendipity is more than that.) In retrospect, I realised that each of the selections I have made can be considered to exemplify a different factor that (without providing an exhaustive list) contributes to the beauty of an experiment, and I have suggested as much in my chapter titles.

In the end, I think there are two key reasons why an exercise like this one could be regarded as rather more than sheer indulgence in the current fad for making lists of ‘greats’ and ‘favourites’. One is that it encourages us to think about just what an experiment is and what role experiments play in the evolution of science. It seems absolutely clear that this role extends well beyond the traditional one of hypothesis-testing. Moreover, in researching the histories of some of these experiments I was made aware of the gap that sometimes exists between the popular notion of how they happened and what they meant, and (as far as it can be discerned at all) the historical reality. Experiments give a concrete framework on which to hang stories about the histories of science – but sometimes those stories come to have a strong element of invention about them, which in itself says something interesting about how we understand both science and history.

The second justification for the exercise is that there is nothing like a list to provoke comment and dissent – and thereby, one might hope, to stimulate debate about how science is practiced and about the goals that it sets for itself. I fully expect to be told how outrageous it is that I have omitted this or that experiment from my choices, or that I have included undeserving candidates. In fact, I look forward to it.