WILKINS LECTURE

Benjamin Franklin: natural philosopher

BY B. F. J. SCHONLAND, F.R.S.

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[Plates 17 and 18]

> 'It is related of Heraclitus, that when his Schollars had found him in a tradesman's shop, whither they were ashamed to enter he told them "Quod neque tali loco dii desunt immortales" that the Gods were as well conversant in such places as in others; Intimating that a divine power and wisdome might be discerned even in those common arts, which are so much despised.'
>
> John Wilkins, *Mathematical Magick* (1648)

The 250th anniversary of his birth is an appropriate occasion on which to review the scientific work of Benjamin Franklin, that versatile genius and 'multitude of men'. His achievements as a natural philosopher fall into three main divisions, the first of which contains his many valuable general contributions to the scientific thought of his day. These occupied much of his spare time throughout a very busy life. They began with a discussion of the causes of earthquakes, published anonymously at the age of 27, and ended with one on the earth's magnetism and geological history, which he wrote at the age of 82. In the second group may be placed his work on the nature of electricity which occupied six all too short years of his middle age. In the third group, which followed the second, lies his bold experimental work on lightning and the electrification of thunderstorms. Since the first two of these subdivisions have been rather fully discussed by others, I shall deal with them in less detail than with the third, the importance and interest of which has not been fully appreciated.

Franklin was the last, the Benjamin, of eight sons born to Josiah Franklin, tallow-chandler of Boston, Massachusetts, on 17 January 1706 (new style). In his boyhood he was taken by his father to watch various kinds of artisans at work so that he might choose the trade he preferred. He wrote in later life that 'it has been useful to me, having learned so much by it as to...construct little machines for my experiments, while the intention of making the experiments was warm and fresh in my mind'. It was he whom Boswell quoted to Johnson as having said that 'man is a tool-making animal'. The great Doctor's comment was, unfortunately, somewhat below his usual standard.

Though Franklin's interest in science and technology began early, it seems to have been the eighteen months he spent in London as a journeyman printer at the age of 19 which kindled in him a strong desire to contribute something to natural philosophy. Here he met Hans Sloane, and saw the collections which were to found the British Museum. Here he made a friend of Henry Pemberton, the popularizer of Newton's work, who was engaged in editing the third edition of the *Principia* and in writing his 'View of Sir Isaac Newton's philosophy'. Here, too, he joined in the discussions of some of the convivial philosophical circles which flourished in that age of intellect and fashion.

Soon after his return to Philadelphia he formed a similar circle, the Leather Apron Club, later known as the Junto, which, during its thirty years under Franklin's leadership, played a very significant part in the development of the American colonies. From it sprang the American Philosophical Society which he thought of as 'a society of *virtuosi* or ingenious men, residing in the several colonies...who are to maintain a constant correspondence...with the Royal Society of London and with the Dublin Society'. And from the Junto came the idea of the Library Company of Philadelphia which made possible Franklin's electrical researches. This subscription library was founded in 1732, with Peter Collinson, Quaker cloth merchant, as its London correspondent and fairy god-father. Collinson was a most distinguished botanist and plant collector, a member of the Penn family and a Fellow of the Royal Society. Long afterwards Franklin wrote that he had sent to the Library Company 'the earliest accounts of every new improvement in Agriculture and the Arts and every Philosophical Discovery, among which in 1746 he sent over an account of the new German experiments in Electricity, together with a Glass Tube and some directions for using it. This was the first Notice I had of that curious subject, which I afterwards prosecuted with some diligence, being encouraged by the friendly Reception he gave to the Letters I wrote to him upon it.' Collinson was a most generous and helpful friend to the Library Company and to Franklin himself for many years.

In 1746 Franklin was 40 years old. He had prospered in a number of business enterprises and was a leading citizen of Philadelphia. His local reputation as an ingenious thinker and inventor was considerable. The time had come when with the aid of his friends of the Junto and the equipment sent by Collinson he was to 'find electricity a curiosity and leave it a science'.

The 'German experiments' were in fact quite remarkable technical developments in electrical equipment. The frictional electrical machine of Hauksbee had been much improved by replacing the hand-held cloth by a spring-loaded earthed leather cushion to press against the rotating glass globe. The charge developed on the globe was collected by light brushes or a chain and passed to a separate insulated conductor where it could be stored. Most important of all was the recent discovery in Germany and in Holland—Franklin's term 'German' covers them both—of the power of the Leyden jar to 'condense' electricity. The Library Company of Philadelphia, aided by gifts from Collinson and Thomas Penn, soon had an electrical laboratory equipped as well as any in Europe. Their electrical machine was demonstrated in England later and adjudged by Lord Charles Cavendish to be more powerful than any seen before; their unique electrostatic motors were strong enough to turn a roasting turkey on a spit.

To work in this laboratory Franklin organized his friends into what must surely have been the first fairly large research team in history. His colleagues were Philip Syng, a silversmith who made most of the apparatus, Thomas Hopkinson, a distinguished lawyer, and Ebenezer Kinnersley, a Baptist Minister. Directing and inspiring the work was Franklin, 'never before engaged in any study that so totally engrossed my attention and my time'. He was careful to give due credit in his publications to the contributions of his friends. In his first letters to Collinson he used the pronoun 'we' throughout the exciting account he gave of 'our electrical inquiries'.

The subject into which they plunged with such enthusiasm can be described as an amusing curiosity whose meaning was a complete mystery. It had only recently become known from the work of Stephen Gray and Desaguiliers that substances could be divided into conductors and insulators. Less than twenty years had elapsed since du Fay had established that electrification was of two types, vitreous and resinous, depending upon the material which was rubbed, and that these were self-repellent but mutually attractive.

The nature of electricity and electrical forces was most obscure. Recent discussions of these questions retained the idea which had originated with Gilbert and was repeated by Newton that insulators were surrounded by invisible effluvia or atmospheres which could be set into vibration by friction, these vibrations creating electricity. Others, particularly from the school of the Abbé Nollet, 'electrician' to the Court of Louis XV, considered electrification by friction to produce an *effluent* stream of an electric effluvium which escaped from the pores of the rubbed body and an *affluent* stream which flowed in from outside to take its place. The prickly sensation felt when a hand was placed near electrified matter was held by Nollet to give evidence of these streams. Light bodies were attracted or repelled according to the particular stream of electric wind in which they happened to lie. Such ideas were far from clear, the experimental evidence for them was poor and they contained nothing which could lead to the further development of the subject. Fifty years ago Rutherford said of them: 'Without detracting in the least from the merits of these philosophers, it is not unreasonable to suppose that the turbidity of their writings was a fair index of the state of their conceptions of electric actions.'

For these vague notions of vibrations in an ethereal atmosphere and of the creation of invisible effluvia Franklin and his group substituted a perfectly simple and direct conception, that of an elementary electric fluid. A year after they had begun their work Franklin wrote 'we had for some time been of opinion that the electric fire was not created by friction, but collected, being really an element diffused among and attracted by other matter'. Their experiments indicated that all bodies had 'a common stock of electricity, which can be added to, or subtracted from by suitable means, causing them to become positively or negatively charged...'. 'Hence', he said, 'have arisen some new terms amongst us; we say *B* is electrized positively, *A* negatively...the parts of the tube or sphere that are rubbed, do in the instant of the friction, attract the electrical fire and therefore take it from the thing rubbing.' This is the first statement of the principle of the conservation of electric charge, that the total quantity of electricity in any insulated system is invariable.

By inventing this one-fluid theory of electricity in which the fluid as an 'element' had a material existence Franklin avoided the very serious difficulty of conceiving of two such fluids, positive and negative, which attract each other and must therefore annihilate each other in coming together. The particles of the single fluid were considered to be attracted by matter but mutually repellent. The repulsion observed between positive or 'over-charged' bodies was in accord with this view. But it could not explain why negatively charged bodies, each deficient in the electric fluid, should repel each other. This was a difficulty which gave rise to discussion and elaborate speculation for many years afterwards. Franklin himself could see no solution to it in terms of a 'model', and thought that it would have to be left as an inexplicable natural law.

Another fundamental contribution made by the Philadelphia school arose in the course of their explanation of the condensing action of the Leyden jar. This they interpreted correctly and for the first time as being caused by the addition or removal of charge from one coating together with the removal or addition of an equal quantity of opposite charge to the other. 'There is really no more electrical fire in the phial after what is called its charging, than before, nor less after its charging.'

In putting forward this explanation, Franklin was for some time not clear how the charge on one coating of the jar repelled a similar charge from the other coating through the medium of the glass. Gradually, however, he saw that it necessitated action at a distance between the particles of the electric fluid, a theory which was supported by later experiments on electrostatic induction made by himself and his young friend John Canton of London.

These new conceptions of the nature of electricity and of electrical forces were derived from ingeniously contrived and lucidly interpreted experiments. The most significant were reported by Franklin to Collinson and through him to the Royal Society. The letters were published in book form and the fruitful ideas so clearly expounded in them drew universal admiration.

The Abbé Nollet, whose name had been omitted from a list of eminent electricians given by the French translator of Franklin's papers, was, however, somewhat upset at the downfall of his theory of effluvia. 'He could not at first believe', said Franklin in his Autobiography, 'that such a work came from America and said it must have been fabricated by his enemies in Paris to decry his system.' Much more generous was William Watson, a very fine electrical experimenter who afterwards became Physician to the Foundling Hospital and was one of the first trustees of the British Museum. Watson independently and without Franklin's knowledge had put forward the same hypothesis of a single all-pervading electrical fluid a few months before the first communication from the group in Philadelphia. But it was he who recommended Franklin's papers to the Royal Society as the work of 'a very able and ingenious man'. 'I think', he said, 'scarce anybody is better acquainted with the subject of electricity than himself.' It may be mentioned in passing that Watson's own publications show that he did not share Franklin's often expressed dislike of vague speculation. He could seriously suggest that insulators were substances like wax, pitch, silk and resin, because these, unlike water and the metals, were not 'in the course of Nature', being the products or excrements of living creatures.

Looking back on the history of electricity it is clear that Franklin's electrical discoveries were very important indeed. The clear and simple hypothesis which he and his friends developed opened a road for much further investigation. The one-fluid theory, with the terms first used by the Junto, is to-day the electron theory of matter. One of Franklin's remarks has a prophetic sound; writing of the electric fluid contained in glass he said: 'It seems as if it were of its very substance and essence. Perhaps if that due quantity of electrical fire so obstinately retained by glass could be separated from it, it would no longer be glass.... Experiments may possibly be invented hereafter to discover this.'

Franklin's group were not particularly elated by their success in this field. Only two years after they had begun he wrote that they were 'chagrined a little that we have been hitherto able to produce nothing in this way of use to mankind'. That they were casting about to find some direct evidence of the identity of lightning and the electric spark is evident from a general paper on the subject which Franklin wrote in 1749. But it was not until 1750 that the crucial experiment occurred to them. Hopkinson in particular had for some time been examining the 'power of points' in discharging conductors and had found that the sharper the point attached to a conductor the more effective it was. They correctly interpreted this as being due to an excess of surface density of electrification. They then turned to the, to them, amazing property of a *separate* earthed point in discharging silently a large conductor even when it was continuously charged by the electrical machine. The conductor gave a two-inch spark when a blunt earthed rod was brought near it but could be discharged silently and completely by a person holding an earthed bodkin a foot away.

Franklin once said: 'Frequently, in a variety of experiments, though we miss what we expected to find, yet something valuable turns out, something surprising, and instructing, though unthought of.' This is what happened when in 1750 the person holding the bodkin was placed on a wax block and was found to become electrified in the same sense as the distant charged conductor.

For the result itself Franklin could at no time offer any explanation at all; he had to leave this 'to the mind of an ingenious reader'. The explanation would have required a combination of the conceptions of electrostatic induction which, as has been said, he had at the time not fully grasped and of the transport of electricity by gaseous ions which was arrived at 150 years later by J. J. Thomson and resembles in fact the 'effluent stream' which Franklin had consigned to limbo. But he saw at once that this experiment was the clue to the thunderstorm problem and that 'this power of points may possibly be of some use to mankind, though we shall never be able to explain it'.

In the next two paragraphs he outlined two proposals, the first 'to determine [by means of an insulated point] whether clouds that contain lightning are electrified or not', and the second to use earthed points to preserve 'houses, churches, ships, etc. from the stroke of lightning' by means of 'upright rods of iron made sharp as a needle and gilt to prevent rusting'. 'Would not these pointed rods', he asked, 'probably draw the electrical fire silently out of a cloud before it came nigh enough to strike and thereby secure us from that most sudden and terrible mischief?'

The first of these suggestions, which was to become known throughout the world as the Philadelphia experiment, was tried out in France two years later. Under the direction of Dalibard an insulated iron rod forty feet high provided with three sharp points was erected, according to the detailed instructions given by Franklin, at Marly-la-ville, six leagues from Paris. During a thunderstorm on 10 May 1752, this rod was found to give a continuous series of sparks to an earthed wire held near to it. The Prior of Marly, who had been summoned by the watch-keeper, wrote that same day to Dalibard: 'Je vous announce, Monsieur, ce que vous attendez; l'expérience est complette...il est sorti de la tringle une petite colonne de feu bleuâtre sentant la soufre, que venait frapper avec une extreme vivacité....'

The Prior repeated the test six times and carefully timed each discharge; he found it to last for the space of one *pater* and one *ave*. Successful repetitions were made that same summer in France and England. Before he had heard about it Franklin was acclaimed in Europe as the modern Prometheus. The discovery was later described by Joseph Priestley, himself no mean judge of scientific experiment, as 'the greatest, perhaps, that has been made in the whole compass of philosophy since the time of Sir Isaac Newton'. The effect on the public mind was awe-inspiring and can be compared to that produced in our own time by the explosion of the first atom bomb.

To Franklin, who had thought a high steeple or a tower necessary for this experiment and had afterwards had recourse to a kite, this success was but the means of proceeding further. Others were marvelling at the ingenuity and the presumption by which he had succeeded in bringing the scientific method to bear upon the phenomenon of such gigantic proportions as the thundercloud, but he himself was turning the French results to good use by setting up an insulated iron rod on his house to measure the sign of the charge on thunderclouds. The rod was broken for six inches in the middle opposite his bedroom door. Each end of the gap was provided with a little bell 'and between the bells a little brass ball, suspended by a silk thread, to play between and strike the bells when clouds passed with electricity in them'. To find the sign of the charge collected by the rod he suggested two methods based on the use of a Leyden jar. The jar could be charged and applied to the insulated part of the rod to test whether the bells rang faster or stopped. Or it could be used to collect the charge on the rod and to compare its sign with that on a rubbed glass tube by means of a cork ball electroscope. The experiment was a dangerous one; one night he found that 'the fire passed, sometimes in very large quick cracks from bell to bell and sometimes in a continued dense white stream, whereby the whole staircase was enlightened as with sunshine'. It was, as this quotation shows, a bold and dangerous experiment. A year later it caused the death of another experimenter, Richmann of St Petersburg.

To his surprise, for he had formed, for once, a rather speculative theory to the opposite effect, he found the majority of the clouds to be negatively charged. This conclusion was supported by further trials by Kinnersley in America, by Canton in England and by Beccaria in Italy. Both Franklin and Kinnersley noticed that towards the end of the passage of a storm overhead the sign of the charge on the cloud altered from negative to positive. All these results are in agreement with observations made within the last thirty years in different parts of the world. Except for a small low-lying positively charged region, which is sometimes evident when the active portion of a thundercloud is directly overhead, the bases of thunderclouds in their mature stages are negatively charged. The negative charge extends to a considerable height, above which is the main positive charge, too far away to diminish appreciably the effect of the negative charge below it. Franklin's observation that the inactive rear of a thundercloud is positively charged has also been confirmed by myself and others. It is presumably due to the descent during the later phase of the storm of part of the upper positive charge.

These ingenious investigations were almost the last that Franklin found time to carry out. But he continued to search for an explanation of the mechanism of thundercloud electrification, and as late as 1762, when he hoped to give some leisure to the subject, he referred to unsuccessful experiments he had made 'to try if negative electricity might be produced by evaporation only'. In this suggestion he was close to what is at present thought to be the true basic mechanism, the freezing of water to ice in the upper regions of the thundercloud. Other processes, including influence mechanisms, friction between ice-particles and the breaking up of the larger water-drops, are perhaps important subsidiary mechanisms taking place lower down, but electrification involved in the change of state from water or water vapour to ice is probably the primary origin of the charge.

Franklin's pointed rod is no museum piece in the history of science; of recent years it has played a significant part in many very useful new devices. Whipple and Simpson have joined it to a recording galvanometer to determine the strength of the electric field in thundery weather from the magnitude of the point-discharge current passing from it. I have done the same with a small tree mounted on insulators. C. T. R. Wilson and Wormell have connected a Franklin point to a very sensitive water-voltameter which separately integrates the currents to and from the tip and so determines the quantities of electricity carried to and from the earth in this manner over long periods. Simpson, Scrase and Robinson have ingeniously arranged for the pointed rod to be carried into the heart of an active thundercloud by small balloons. The sign and the rough magnitude of the charge collected are then shown by the coloured stain produced on a piece of chemical pole-finding paper touching the base of the rod and rotated past it by clockwork.

The great reputation which Franklin gained from the success of the Philadelphia experiment was naturally linked in the popular mind with his second proposal; the idea of the lightning rod. But other electrical authorities, though they applauded his demonstration of the identity of lightning and the electric spark, were not prepared to concede that a single earthed rod could quietly discharge a thundercloud. The Abbé Nollet pointed out 'the enormous gap between the experimental fact and the conclusion that was hopefully drawn from it'. 'Some people', he complained, 'have even stated that protection from lightning when travelling in open country can be secured by holding a sword above one's head. Clerical gentlemen who carry no swords are beginning to object that this puts them at a disadvantage...though according to the French edition of Franklin's book, the

Bible of the day, one could do without the power of points if one arranged for one's clothes to be thoroughly soaked.' An English expert, Benjamin Wilson, thought the proposal was like equating 'the fire and crackling of a few chips to the rage of Vesuvius'.

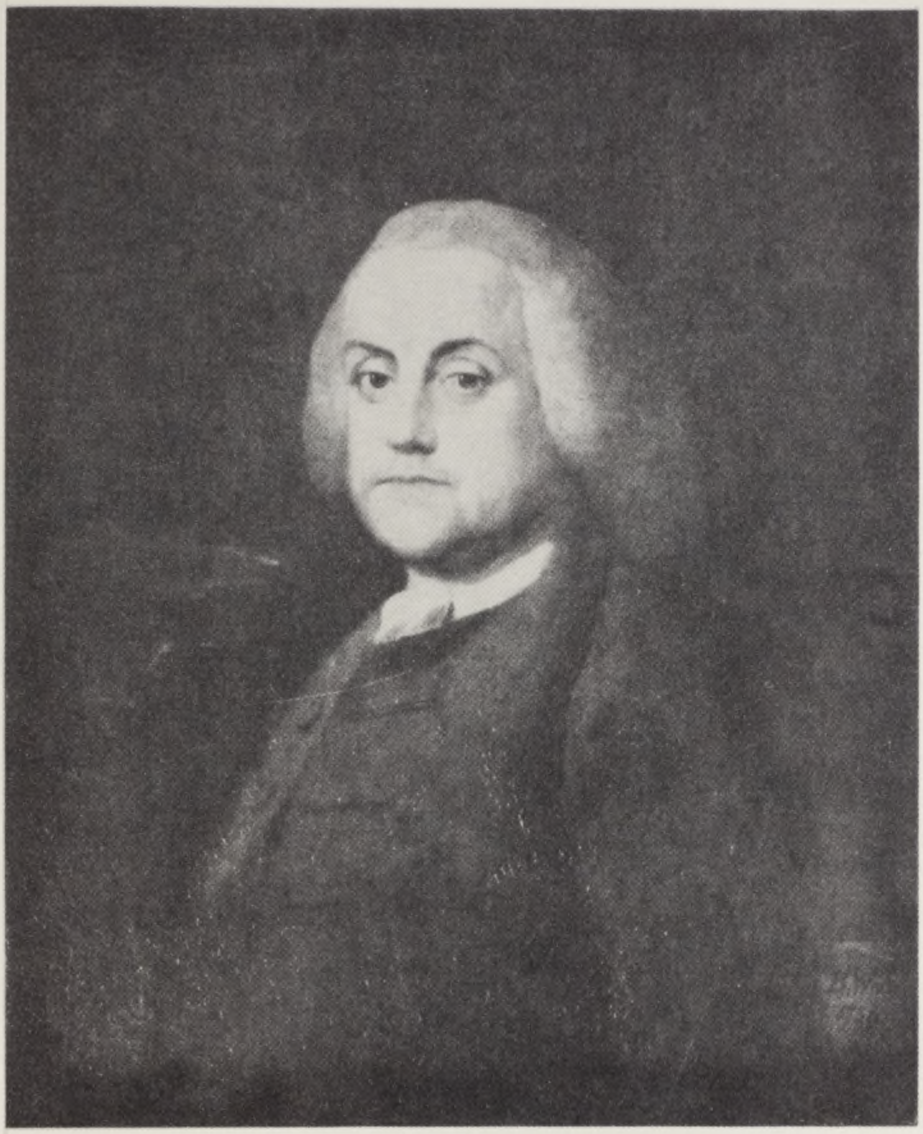
To this and similar criticism Franklin replied that his lightning rod proposal as further developed by him and tried out in model experiments involved two quite separate ideas. The rod should either prevent a stroke altogether or if a stroke did occur, should attract it and conduct it safely to ground. He was not yet sure which function would be the most important. Even in 1772, twenty years later he held his ground and wrote 'I cannot but conceive that a number of such conductors must considerably lessen that [i.e. the charge] of an approaching cloud'.

There remained the quite reasonable possibility that the rod might be too successful in attracting lightning. Benjamin Wilson, a leading advocate of this view, held that Franklin's proposal might 'be promoting the very mischief we mean to prevent', and recommended 'that conductors should not only be rounded at their ends but made considerably shorter...and indeed should not exceed the highest part of the building'.

The violent controversy which developed, the argument known as 'knobs *versus* points', has been described in detail elsewhere. It began with a committee appointed by the Royal Society in 1772 to recommend means of protecting the powder magazine at Purfleet. Only three years before this, lightning had set off a gunpowder explosion which destroyed one-sixth of the city of Brescia and killed three thousand people. The majority of the committee, which included Franklin, who was in London at the time, Cavendish and Watson, recommended putting up properly earthed pointed conductors according to a detailed specification. In a minority report Wilson objected to the points and suggested that knobs should be placed on top of the rods to reduce 'their great readiness to collect the lightning in too powerful a manner'.

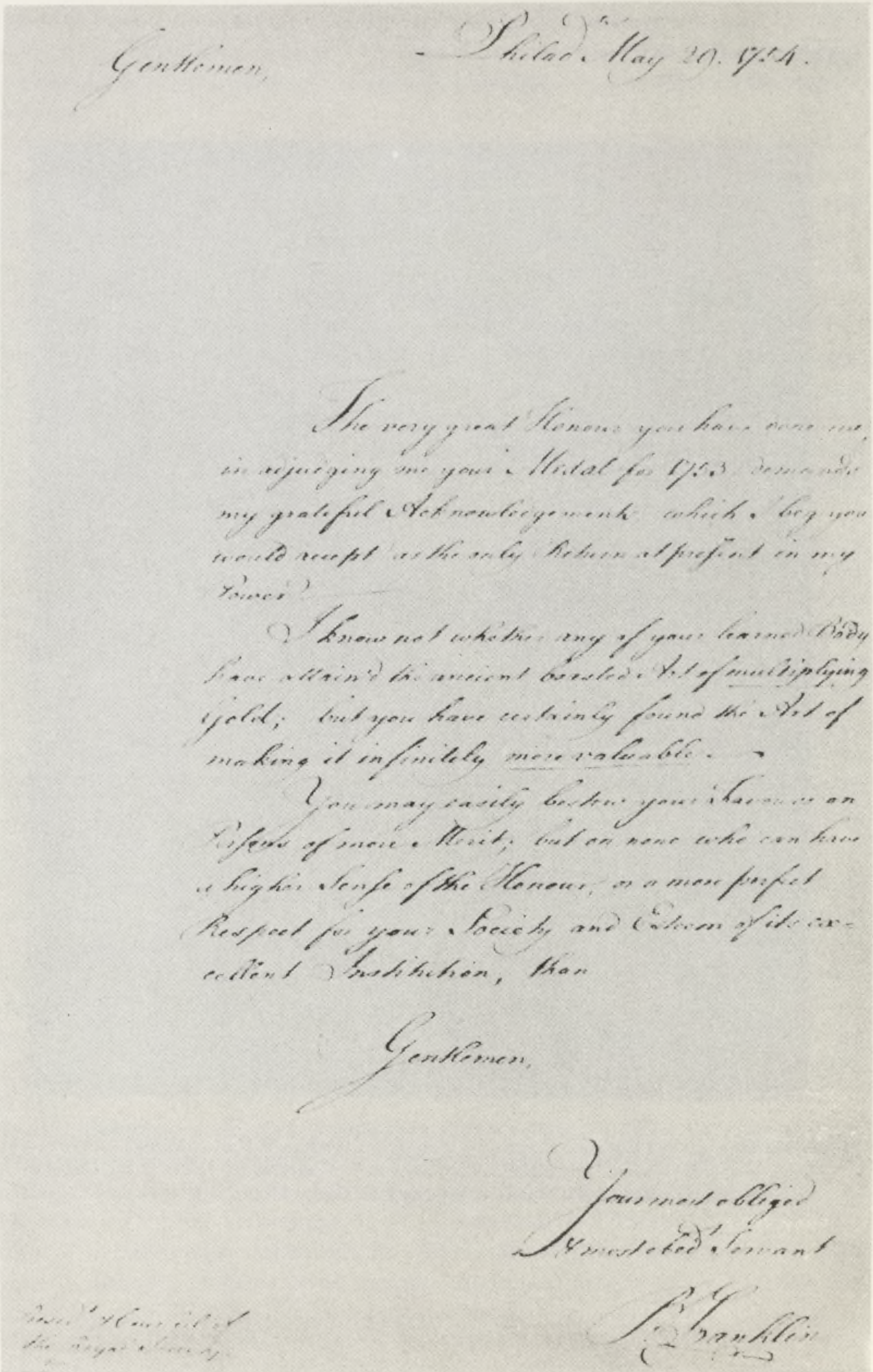
Wilson, who was concerned in this matter both as electrical adviser and as official painter to the Board of Ordnance, has been rather unfairly treated for his part in this argument. There was, indeed, a real chance that lightning rods would attract too many discharges, a serious matter in the case of a powder magazine. Some of these discharges might produce side-flashes to metal objects, and others might be attracted towards the rod but on closer approach deviate to the building itself, as, indeed, one did at Purfleet itself a few years after the rods had been put up.

Wilson therefore made a very thorough study of the possible over-effectiveness of rods by extending Franklin's experiments with a model cloud and a model building. His electrified cloud was no less than 155 feet long and a foot and a half in diameter. Of horse-shoe shape, it was suspended by silken cords in the Great Room of a fashionable dance-hall in Oxford Street (The Pantheon, 'the New Winter Ranelagh', 'a place so universally patronized that even Dr Johnson was to be found there'). Wilson considered that his results, which were forwarded to the President of the Royal Society by the Office of Ordnance in November 1777, completely vindicated his views. George III, who had given Wilson the appointment



Portrait of Benjamin Franklin, F.R.S., by Benjamin Wilson, F.R.S., painted in 1759. Taken from Franklin's house by Major André, carried to England by General Sir Charles Grey and returned in 1906 to the United States by Earl Grey. Now hanging in the White House.

(*Facing p.* 440)



Gentlemen,

Philad.a May 29. 1754.

The very great Honour you have done me, in adjudging me your Medal for 1753, demands my grateful Acknowledgements, which I beg you would accept as the only Return at present in my Power.

I know not whether any of your learned Body have attain'd the ancient boasted Art of multiplying Gold; but you have certainly found the Art of making it infinitely more valuable.

You may easily bestow your Favours on Persons of more Merit; but on none who can have a higher Sense of the Honour, or a more perfect Respect for your Society and Esteem of its excellent Institution, than

Gentlemen,

Your most obliged & most obed.t Servant

B Franklin

Photograph of a letter from Benjamin Franklin in the possession of the Royal Society. (Actual size 12 × 8 in.).

of Sergeant Painter after the death of Hogarth, himself said that they would have convinced 'even the applewomen of Covent Garden'. Such model experiments, as we now know, have little validity because the conditions which in practice prevail between cloud and ground are not easily scaled down. But the question had by then ceased to be a scientific one. Advocates of pointed rods were identified with the insurgent American colonists and considered to have rebel sympathies. Points were removed by Royal command from the lightning rods on all Government buildings.

Wilson was right in thinking that blunt rods were every bit as good as points but wrong in suggesting that they were better. On the great scale of the natural phenomenon both would be equally effective. Both Wilson and the Abbé Nollet were in error in suggesting that the installation of lightning rods was dangerous, for experience over two centuries has shown that the rod gives nearly complete protection for a distance equal to its height above surrounding objects.

We have become so used to the protection afforded by Franklin's rod that its value is often forgotten, sometimes even questioned. The voluminous history of damage and destruction to churches and wooden ships before it was introduced shows clearly why it was hailed at the time as such a boon to mankind. In London, the steeple and roof of St Paul's Church were set on fire and destroyed in a thunderstorm in 1561, the steeple of St Bride's was severely damaged in 1764 and that of St Martin-in-the-Fields as late as 1842, when it was still unprotected by a conductor. The Campanile of St Mark's in Venice was twice completely destroyed and seven times severely damaged between 1388 and 1766. In sixteen years, from 1799 to 1815, there were 150 cases of lightning damage to vessels of the British Navy. Nearly 100 lower masts of line-of-battle ships and frigates were destroyed; one ship in eight was set on fire in some part of the rigging or sails; about 70 seamen were killed and more than 130 seriously hurt from this cause. In ten cases the ships were completely disabled and compelled to leave their stations at critical periods in the Napoleonic wars. Several ships were lost with all hands in violent thunderstorms.

The lightning rod is still essential for the protection of all factories which make or use explosives. In the more thundery parts of the world its value in preventing the destruction of ordinary houses by lightning is attested by the best of all judges, the fire insurance companies concerned. It is widely used for the protection of high-voltage electrical supply systems, where it takes the form of one or more earthed wires stretching from pylon to pylon to protect the power lines below. In a recent application to fast aircraft it reverts in function to the silent discharge of a conductor which Franklin and his friends first investigated. Such an aircraft is frequently highly charged in its passage through clouds. It would release this charge violently and spasmodically with consequent interference with wireless communication, were it not for the continuous discharging action of a number of points in the form of metal-wire pigtails attached to the trailing edges of the wings of the machine.

As to the manner in which the rod provides protection for buildings and power-lines, Franklin's original suggestion that point discharge might prevent a thunder cloud from building up a dangerous charge does not hold except for rods which are very much higher than he thought necessary. But the tall Empire State Building in New York and the Washington Memorial do act in just this way. Many discharges between them and overhead clouds start as upward-moving streamers which after reaching the cloud remove its charge continuously without brilliant intermittent processes of any kind. The average current in such discharges is only about 80 A, compared with 50000 A in the more usual flash to ground. It lasts for as long as 0·6 s, and observers state that little or no thunder can be heard. It is in fact Franklin's 'silent discharge'.

The continuous type of flash from ground to cloud is, however, not observed from rods of ordinary height. Here the first step is the downward movement of a streamer from cloud to ground. Breakdown processes inside the cloud first cause negative charge to be lowered into the air on the conducting stem and branches of a leader streamer. These charged branches as they approach the earth set up strong electric fields at the ground, sufficient to draw positive streamers from nearby projecting objects.

The length of the upward streamer will depend upon the height of the projection from which it starts. A lightning conductor on a house may give rise to a streamer fifty feet long which then makes contact with the leader and enables its charge to be passed to ground extremely rapidly, the peak current sometimes reaching 100000 A. The protective value of the lightning rod lies in its ability to produce a longer junction streamer than any lower projection, such as an adjacent chimney, and to carry safely to earth the heavy current in the rapid return stage of the discharge.

Although he hoped to do so, Franklin's busy life never permitted him to repeat the seven or eight exciting years he had spent as an experimenter. In 1757 he moved from Philadelphia to live in London for eighteen years, with one intermission of a little over a year. His public work during the latter part of this period is best summarized in the words he wrote to Lord Howe: 'Long did I endeavour, with unfeigned and unwearied zeal, to preserve from breaking that fine and noble China vase, the British Empire; for I knew that being once broken, the separate parts could not retain even their share of the strength or value that existed in the whole, and that a perfect reunion of those parts could scarce ever be hoped for.'

Throughout his life he continued to keep in close touch with electrical studies (and with experience of lightning protection), and he was guide, philosopher and friend to many younger men working in Europe and America. Amongst those who carried electrical research significantly further and were directly encouraged by him were John Canton, the brilliant schoolmaster of Spital Square who finally established the principles of electrostatic induction; Joseph Priestley, the chemist, who confirmed Franklin's finding that there is no electric field inside a nearly closed conductor and was the first to show that this implied an inverse square law of force for electrical repulsion; Giovanni Beccaria, the teacher of Galvani and the first to show chemical decomposition by the electric current; and Franklin's old colleague, Ebenezer Kinnersley, who continued to conduct research after the breakup of the Junto group and made important studies of the heating effect of the electric discharge.

Franklin's correspondence gives a vivid impression of the breadth of his interests in pure and applied science and of the help he gave in forwarding new projects. He was, for example, keenly interested in the proposal of the Royal Society to measure the gravitational attraction of mountains and corresponded with de Saussure of Geneva on this subject. The best known of his own inventions are the Franklin Stove or Pennsylvania fireplace and bifocal spectacles. One other is of some interest, since it links the Society and himself with the world of music. During his second stay in London, Franklin saw Delaval demonstrate at the Society the water-tuned musical beer glasses which had been invented by Puckeridge in 1743. These were played by passing a wet finger round their brims. He was 'charmed by the sweetness of its tones' but not by the cumbersome method of playing. With the zest of his earlier days he set to work to develop a more convenient instrument. The beer glasses he replaced by glass hemispheres of varying diameters, thirty-seven in all, finely tuned by grinding. To obtain relative motion he mounted these on a horizontal iron spindle running through holes in their centres and turned by a belt and treadle. The player had then merely to touch the moving glasses with the fingers or a light drum-stick to bring out the tones required. The instrument, which had a wide vogue for 30 years, was called by him the Armonica. Its construction and manipulation and even the playing of it absorbed him as completely as had done his electrical researches. The Harmonica, as it came to be called, was speedily improved by the addition of a keyboard and both Mozart and Beethoven composed music for it. Mozart wrote for it, nine months before he died, a beautiful work, the Adagio and Rondo in C for harmonica, flute and oboe.

The Royal Society awarded its Copley medal to Franklin in 1753. Three years later he was elected a Fellow on the motion of William Watson. He served four times as a member of the Council, in 1760, 1765, 1766 and 1772. He was awarded one of the medals struck to commemorate the last voyage of Captain Cook, for whose ship 'under the conduct of that most celebrated navigator' he had arranged safe passage during the War of Independence.

David Hume, one of his numerous friends in this country, once wrote to him: 'America has sent us many good things, gold, silver, sugar, tobacco, indigo: but you are the first philosopher and the first great man of letters for whom we are beholden to her.' Others have followed Franklin but few have surpassed him.

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Generalized functions and Dirichlet's principle

By G. Temple, F.R.S.

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This paper gives a simple proof of Dirichlet's principle for any bounded domain. The method is to show that any 'minimizing sequence' represents a generalized function u, which is proved to be harmonic and to be equivalent to an ordinary numerical function.

1. Introduction

Dirichlet's principle is not only a fruitful topic of research in analysis and topology but also a result of cardinal importance in applied mathematics. The purpose of this paper is to provide a proof of Dirichlet's principle using concepts and methods which are of established significance in modern applied mathematics.

One method of achieving this result is to employ the method of orthogonal projection invented by Zaremba (1927) and perfected by Nikodym (1933), Weyl (1940) and Gårding (1953). But for the applied mathematician, Dirichlet's principle is primarily a problem in the calculus of variations, and accordingly we envisage the problem in this paper as the minimizing of Dirichlet's integral.

The integrals which have to be considered are all quadratic functionals of two functions u and v of the forms

$$\int \operatorname{grad} u \,.\, \operatorname{grad} v \, d\Omega, \quad \int u \operatorname{grad} v \, d\Omega \quad \text{or} \quad \int uv \, d\Omega,$$

taken over a domain Ω, and this suggests that the appropriate technique is the method of distributions (Schwartz 1950, 1951), or the equivalent method of