Oliver Heaviside (1850-1925) — Physical Mathematician

D. A. EDGE, AFIMA
The Mary Erskine School, Edinburgh

> Mathematics is of two kinds, Rigorous and Physical. The former is Narrow: the latter Bold and Broad. To have to stop to formulate rigorous demonstrations would put a stop to most physico-mathematical enquiries. Am I to refuse to eat because I do not fully understand the mechanism of digestion?
>
> Oliver Heaviside

Preface

Too little attention is paid on educational courses in mathematics and science to the personalities of the great innovators. When teaching at Paisley College of Technology I was very impressed with the tape-slide facilities in the library and I thought that here was an ideal way of presenting biographical material. Not only would well-prepared material be instructive but also it would be entertaining.

I was inspired to produce a tape-slide presentation on Oliver Heaviside in particular by an excellent radio talk by Dr. D. M. A. Mercer.[1] The essay below is along the lines of my script and is presented with a view to interesting others in Heaviside and perhaps in the idea mentioned at the outset.

Summary

There are many misconceptions about Oliver Heaviside. He had a delightful and noble character though these features were obscured by his apparently hermit-like way of life. He was self-taught and retired from work as a telegraphist in his early twenties to devote himself to experimentation and writing. He made no money from his epoch-making discoveries and lived and died in near-poverty.

He is responsible for Maxwell's Equations as we know them and he extended the theory of electromagnetic wave propagation. He established the mathematical theory of telegraphy and telephony and formulated the condition for distortionless transmission of speech. He found the mathematics of his time unsatisfactory for solving many important problems and consequently invented the operational calculus which he used to great effect. He predicted the possibility of a reflecting layer in the upper atmosphere (the Kennelly-Heaviside layer) and he was very interested in terminology and coined and defined many new words (e.g., inductance).

Details

Oliver Heaviside was the youngest of four sons of Thomas Heaviside, then at 55 King Street, Camden Town, London. His mother was formerly Rachel West, who had been a governess in the Spottiswoode family and whose sister was the wife of Sir Charles Wheatstone, the telegraphist and prolific inventor. Thomas Heaviside was a skilful wood-engraver who moved to London from Teesside with his wife and young sons in about 1849. Oliver was born on May 18th, 1850.

It has been suggested[2] that the Heaviside family moved to London because the development of photography was making wood-engravers redundant and there were better prospects of employment in the capital. It seems that the family experienced hard times during Oliver's youth and for a while his mother ran a school and subsequently let rooms.[3] The high quality of Thomas Heaviside's work is evident in an engraving of a drawing by Godwin (reproduced in reference 2). A brother of Thomas was an artist and engraver still more capable, and from two of Oliver's drawings (at age 11) reproduced in reference 2 he was at least a budding artist.

Oliver Heaviside attended Camden House School and did well in his examinations, taking a prize for top place in natural sciences. However he got a bad mark in geometry – probably because he disagreed with the way it was taught to small boys. He left the school in 1866 but his uncle, Professor Wheatstone, advised him to continue to study (in particular French, German, Danish and Natural Sciences). Also the youthful Heaviside did experimental work on electromagnetism and taught himself Morse Code.

In 1868 he started work with a Danish telegraph

company at Fredericia in Denmark. In September of that year the first Anglo-Danish cable was laid and Heaviside was involved in various tests on the line. He observed a number of anomalous effects which he confessed he could not understand at all – but then neither could anyone else. In 1870 he was promoted and based at Newcastle-upon-Tyne, the Great Northern Company having taken over the Danish company. Between 1870 and 1874 Heaviside was at Newcastle and he cooperated with his brother Arthur who was an engineer then with the Post Office at Newcastle.

In 1873 Heaviside obtained a first edition of Maxwell's famous treatise "Electricity and Magnetism." He was profoundly impressed and subsequently became the principal exponent of Maxwell's ideas. Heaviside cleared away the debris of the battles fought by Maxwell in establishing these ideas against the older theories, and he reduced Maxwell's maze of symbols practically to just two: viz., electric and magnetic force. Thus Heaviside established symmetry throughout the whole of electromagnetism and the present form of Maxwell's Equations is due to Heaviside. Fitzgerald in reviewing Heaviside's collected "Electrical Papers" wrote: "Since Oliver Heaviside has written the whole subject of electromagnetism has been remodelled by his work. No future introduction to the subject will be at all final that does not attack the problem from at least a somewhat similar standpoint to the one that he puts forward." On the other hand H. J. Josephs has pointed out[4] that although he is of the opinion that the so called Maxwell's Equations should be called Heaviside's equations this is "not merely because the formulation is Heaviside's but also because they are less general than the proper Maxwell's Equations which are best expressed in quaternionic notation."

In 1874 Heaviside was elected an Associate Member of the Society of Telegraph Engineers. (Later, this Society became the Institution of Electrical Engineers.) He left the Great Northern Company and returned to London to live with his parents at 117 Camden Street, St. Pancras, and it was here that he did most of his original work.

He liked to study mathematics in the quietest part of the day (from 10.00 pm into the small hours) and during the day proper he conducted experiments. He had begun to publish in 1872, and from 1874 onwards he published numerous articles (though not without encountering difficulties with editors or referees).

In 1876 he was fairly well known (though not well understood) and regarded as a prominent scientist. He was elected to the Council of the Society of Telegraph Engineers (though he did not attend a single meeting and was not re-elected the following year). At this time William Preece was also a member of the Council; Heaviside and Preece were to cross swords at a later date. In 1881 Heaviside was unable to pay the subscription of the Society of Telegraph Engineers and he was struck off the register. Despite this apparent shortage of money he turned down a well-paid appointment made available by Preece with the Western Union Company.

Early in his studies at Newcastle, Heaviside had discovered the method of analysing alternating current using the rules for direct current circuits and impedances $j\omega L$, $1/j\omega C$, etc. Steinmetz and Kennelly made these complex quantities familiar but Heaviside deserves as much credit as these two men. Subsequently he established the method of analysing alternating currents which is in use today. During the early course of his studies he developed the operational calculus, using the multiplier $1/p$ to represent integration and the multiplier p differentiation. In the course of subsequent analysis he had to find interpretation for such as $1/\sqrt{p}$. It seems that Heaviside was unaware that "fractional differentiation" was an old subject which had been introduced by Leibniz in 1695 and developed by such great mathematicians as Euler, Liouville, Gregory and Kelland. Heaviside, it should be remembered, was self-taught and had very limited access to the work of earlier mathematicians. Despite this he developed the subject of fractional differentiation much further in some directions than any of his illustrious predecessors.[4] Although Heaviside was successful the pure mathematicians of the day did not like his methods.

He had enormous physical insight which he used freely: the mathematicians were averse to this, they wanted rigorous analysis. Sir Edmund Whittaker[3] quoting a contemporary pure mathematician writes: "there was a sort of tradition that a Fellow of the Royal Society could print almost anything he liked in the *Proceedings* without being troubled by referees: but when Heaviside had published two papers on his symbolic methods, we felt that the line had to be drawn somewhere, so we put a stop to it." Heaviside was deeply offended. He spoke in private of the wooden-headed Royal Society mathematicians and wrote scathingly that good mathematicians, when they die, go to Cambridge. In 1904, after Heaviside's methods had borne such obviously good fruit, the Council of the Royal Society decided to offer him the Hughes Medal. He declined it (privately).

By 1887 Heaviside had done his main original work and in 1889 he moved with his parents to Paignton, Devon, to live in a house taken by his brother Charles who had become quite successful in helping to run a music business in Torquay. About this time Heaviside entered the last phase of his scientific life. This consisted mainly of publishing his collected papers in two volumes,[5] and his three-volume "Electromagnetic Theory."[6]

In 1894 his mother died, to be followed in 1896 by his father, and the following year he rented a house at Newton Abbott (near to both Paignton and Torquay).

Heaviside, then, was at Paignton from 1889 to 1897. Towards the end of 1957 a collection of his papers was found under the floorboards of his room in the house where he lived. The many documents filled three sacks and were scrutinised by H. J. Josephs.[4] Mr. Josephs found that most of the collection was associated with the publication of Volumes 1 and 2 of "Electromagnetic Theory" but there were many other issues dealt with. For example, harking back to the dispute about operational calculus and fractional differentiation it seems that Heaviside further analysed his own approach and achieved a different interpretation of his parameter p which would have allowed him to construct a rigorous mathematical basis for his work. He did not bother.

For the first 2 years at Newton Abbott (1897-1899) he retained the elderly housekeeper who had been with his parents at Paignton, but then she had a stroke and had to leave him. From 1899 he worked and lived in solitude and suffered from ill-health. Perhaps because of these new circumstances it is too easy to get the impression from some sources that Oliver Heaviside was a bitter recluse with a twisted personality. This is quite untrue. There are, in the Heaviside collection at the Institution of Electrical Engineers, Savoy Place, London, the negatives of some photographs of Heaviside taken about 1890, shortly after the move to Paignton. They are printed in reference 2 and one of the photographs was used for a posthumous portrait by Francis Hodge. This portrait hangs in the Heaviside room at Savoy Place and is reproduced in reference 7, although not in colour. The photographs were taken by Heaviside's nephew Charles, son of his brother of the same name. They show Heaviside to be a strikingly handsome man, which according to various reports he remained to the end of his life. It was about the time the photographs were taken that Dr. G. F. C. Searle became friendly with Heaviside. Searle, subsequently with his wife, visited him on many occasions up to the end of his life and it is chiefly to Searle that we are indebted for an account of the real Heaviside (reference 7, pp. 8–9 and 93–96).

Heaviside and Searle (who was 14 years his junior) used to go for cycle rides in the nearby countryside and it seems that Heaviside occasionally tore ahead by putting his feet on the handlebars, folding his arms and letting the bike race down steep slopes. (In those days braking facilities on bicycles were primitive and many lanes would be merely cart tracks.)

There is another photograph printed in reference 2 which is of interest. It is probably contemporary with the other photographs and shows a group which is mostly the Heaviside family. (It includes mother, father and brothers, Arthur and Charles.) Also in the picture is Charles' sister-in-law, Miss Way, of whom more in a moment. At the back of the group, peeping out from a central position, is Oliver – bright eyed, casually confident and smoking a pipe. The effect is surreal. Apparently he detested alcohol in all its forms but liked a pipe of the strongest tobacco. He liked walking and cycling and was a good gymnast but when working he was the reverse of a fresh-air fiend. He would close doors and windows, light a gas fire and an oil stove, and puff away at his pipe. Visitors found it rather uncomfortable but he loved it.

In 1908 Heaviside was offered a home by Miss Way. This was not a romantic move but a practical one. Heaviside had been living alone for about 8 years, he was an incompetent cook and had suffered generally with his health, having had a bad attack of jaundice at Christmas 1907.

Miss Way's house was Homefield, Lower Warberry Road, Torquay, and she gave up to him the upper part of it. He was a paying guest at the rate of £100 p.a. At the time he was 58 years old and she about 66 years of age. He lived at Homefield until 5 weeks before he died, at a nearby Nursing Home. From 1916 to 1925 he was alone.

He was without doubt an oddity, a strong-minded individualist, but never remotely insane nor dominated by a sense of bitterness. He had a great sense of humour and Searle tells of many occasions when he demonstrated this.[7]

He was not quite the recluse that one might expect; although he would never leave his home to visit others (family excluded), he was always delighted to receive visitors himself and would scan the visitors' lists in the newspapers for names of holiday-makers in the local area. His visitors included many prominent scientists, by whom he was highly regarded.

One visitor was J. S. Highfield who was President

of the IEE in 1921. This was the 50th year of the Institution's foundation and one of the events in celebration was the creation of the award of the Faraday Medal. It was decided that Heaviside should be the first recipient and the President himself journeyed to Torquay to make the formal presentation in September 1922. Heaviside was then 72 years old.

When he was elected FRS in 1891, Heaviside would not travel up to London for the installation. Despite this apparent reticence he had a wide scientific correspondence with the foremost men of the day. Hertz, for example, was his friend although they never met. A special friend was G. F. Fitzgerald of University College, Dublin – the two men met only twice, for short periods. Fitzgerald, like Maxwell, died before he reached 50 and Heaviside dedicated Volume III of "Electromagnetic Theory," "In memory of Geroge Francis Fitzgerald, FRS – 'we needs must love the highest when we' know him."

The three volumes of "Electromagnetic Theory" were published in 1893, 1899 and 1912, respectively. In the Heaviside Collection at Savoy Place there is the following poem, in Heaviside's own handwriting, in pencil on the flyleaf of Volume I.

DEDICATION
To My Dear Children

I did not send you any cards,
For I had none to send,
So now I send you this here book,
Whereby to make amend.

The first chap. is for Freddie,
And may he always be,
A credit to his parents,
And an ornament to Torquay.

The next chap. is for Ethel,
And may she read it well,
And study it, and find it good,
Nor think the book a sell.

The third chap. is for Charlie,
And may he never be,
A terror to his parents,
And a torment to Torquay.

The fourth chap. is for Rachael,
Because it is the best,
And may she never *never* try,
To turn it into jest.

The preface is for Beatrice,
Because it is so short,
And may she never *never* think,
It all amounts to nought.

The contents are for Pa and Ma,
And may they never know,
The pangs of tortured conscience,
Or the awful depths of woe!

This volume must have been given by Heaviside to his brother Charles' family.

Heaviside kept notebooks concerning papers that he wrote and these are now preserved at Savoy Place. The handwriting is neat and the books are tidy; an editor once wrote to him: "No other contributor can approach the admirable clearness of your copy and the cleanness of your proofs." In the notebooks are not only précis of the papers but also comments about the reception they met with. For example, concerning his first paper in the *Philosophical Magazine* of February 1873, "On the Best Arrangement of Wheatstone's Bridge"* he observes that Sir William Thomson (Lord Kelvin) mentioned it when they met at Newcastle a very short time after it appeared and so Heaviside sent him a copy. He also sent Maxwell a copy and observes in the notebook that Maxwell noted it in the second edition of "Electricity and Magnetism." Heaviside comments that for his first paper in the *Philosophical Magazine* it was a good beginning.

In the latter half of the nineteenth century there was a good deal of interest in terminology in general and in units in particular. As an innovator Heaviside often had to think carefully about the use of words to describe his ideas. In his writing he used a style uniquely his own: always precise and often refreshingly humorous.

One of Heaviside's major achievements was to establish the importance of inductance in telegraphy and telephony, but he had a big struggle convincing other workers that he was right. Inductance is an important factor in getting the correct balance such that the attenuation of all frequencies is the same and signal distortion avoided. This was the main bone of contention between himself and William Preece. Unfortunately Preece walked the corridors of power and Heaviside did not, so it was the latter who got the worse of the struggle at the time – his punishment being that he was denied access to the scientific press for a little while.

In June 1887, Heaviside published one of his articles in his series "Electromagnetic Induction and

* Heaviside was anything but a sycophantic name-dropper and certainly would not have chosen his title or his topic because of its connection with his uncle, Sir Charles Wheatstone. As a matter of fact, prolific inventor though Wheatstone was, the bridge was not invented by him (but by S. H. Christie, in 1833, as Wheatstone more than once pointed out). Wheatstone's name became associated with the bridge because of his frequent use of it.

its Propagation" in *The Electrician*. He commented that the results in this paper were originally scheduled to appear in a paper by his brother Arthur but his contribution was blocked "by the eminent scienticulist*, W. H. Preece, FRS, in the Spring of '87" the grounds being "irrelevancy and want of novelty." The paper concerns attenuation and distortion in submarine cables which were by no means irrelevant topics and were certainly novel as Heaviside sought to correct Sir William Thomson's theory, and incidentally some inaccurate estimates by Preece. (It should be added that Sir William Thomson was aware of the limitations of his theory, in the way that all great pioneers are.)

In September 1887 Heaviside submitted an article "Mr. W. H. Preece on the self-induction of Wires." It was not published then but had to wait inclusion in his "Electrical Papers" (reference 5, Volume II, pp.160–165) of 1892. Understandably it was not published, for Heaviside did not restrain himself:

> "... It will be remembered that Mr. Preece, in spite of the well-known influence of resistance in lowering the speed of signalling, was formerly an advocate of thin wires of high resistance for telephony; but that, perhaps taught by costly failures in his own department†, and by the experience of more advanced Americans and Continentals who had signally succeeded with wires of low resistance, he recently signified his conversion. Along with this however, it will be remembered that, although it had been previously shown how very different the theory of the rapid undulatory currents of telephony is from the electrostatic theory of the submarine cable, he adopted rather pronouncedly what should, it appears, be understood to be the electrostatic theory, with full application to telephony. It is not to be presumed that Mr. Preece meant to deny the existence of magnetic induction, but that he meant to assert that it was of so little moment as to be negligible. It will also be remembered that his views were rather severely criticised by Prof. S. P. Thompson, and that Prof. Ayrton and others pointed out that he had not treated the telephonic problem at all. More recently still, it may be remembered by the readers of this journal that it has been endeavoured to explain how and why the electrostatic theory has so limited an application to telephony (E.M.I. and its P., section XI *et seq.*) [reference 5, Vol. II, pp. 119–155]. Nothing daunted, however, Mr. Preece now, although to some extent modifying his views as regards iron wires, maintains that self-induction is negligible in copper-wire circuits; and in fact, on the basis of his latest researches, asks us to believe that the inductance of a copper circuit is *several hundred times smaller* than what it is maintained to be by experimental theorists, and is really quite negligible in consequence ... "

Support for Heaviside's views on the importance of inductance in distortionless transmission came from the United States in the person of Professor Michael Pupin. In 1900 Pupin published the results of some brilliant experiments verifying (13 years after they were made) Heaviside's conjectures. In his paper[8] Pupin points out the analogy between the effect of inductance coils in telephony (when transmitting electromagnetic waves) and the effect of weights on a string (when transmitting displacement waves), the inductance in the former case corresponds to momentum in the latter. Pupin had to calculate the best positions at which to insert the discrete inductance coils; this was a mathematical problem which hitherto had not been solved. After Pupin had gone on to demonstrate physically that Heaviside was correct it became standard practice to add inductance to (*i.e.*, "to load") the many land lines and submarine cables that were laid at the beginning of this century. Initially discrete loading was the practice but with improvements in cable manufacturing techniques this was succeeded by continuous loading. Modern telecommunications systems do not use loading because a loaded line behaves like a low-pass filter and nowadays high frequency transmission systems are in use to cope with the great volume of traffic.

Heaviside also concerned himself with the theory of electromagnetic waves in free space and as a result of his calculations, and in the light of Marconi's radio transmission across the Atlantic in 1901, he suggested the possibility of a reflecting layer in the upper atmosphere. A. E. Kennelly made a similar suggestion in that same year, 1902, and their prediction was verified directly some 20 years later by Edward Appleton.

Although Heaviside concerned himself largely with practical problems of fairly immediate importance he did at times take interest in what he must have regarded as purely theoretical problems, e.g., the rigorous mathematical basis of the operational calculus. A slightly different type of theoretical

---

* Scienticulist was Heaviside's coined word used to refer disparagingly to those who affected to be scientists but were not truly so.

†W. H. Preece worked for the Post Office becoming Engineer-in-Chief and Electrician 1892–99. He was created KCB in 1899.

problem that he investigated, which is now a very practical problem, was the transmission of signals through waveguides and coaxial cables. He made a wide range of contributions to the field of electromagnetism and in addition gave attention, in a disconnected fashion, to a very large number of ancillary topics – so many, in fact, that the mere listing of them would take up a considerable space. Some of the less weighty and less esoteric topics were: the age of the earth (a subject dear to Lord Kelvin); what is now known as a low-pass filter; and the teaching of mathematics. In this last connection one topic that concerned him deeply was that of vectors (see Preface to reference 5, pp.xi–xii): and these especially in preference to quaternions since they had no physical interpretation whereas vectors quite clearly had.

His approach to mathematics was pragmatic. He regarded it as an experimental science – in fact he wrote an article with just such a title (reference 6; Volume II, pp.1–12): first get on in any way possible and let the logic be left for later work – a view subsequently expressed by Einstein and G. H. Hardy. Despite the rough handling he received from the Cambridge mathematicans of about 1890 his article on mathematics as an experimental science (first published in 1894) was generous to what one might call "the true spirit" of Cambridge. He comments that "even men who are not Cambridge mathematicians deserve justice, which I fear very much they do not always get."

Some writers suggest that Heaviside retired at an early age because of deafness. This seems not to be entirely credible. His deafness appears to have been intermittent and certainly did not stop him indulging his love of music. He owned an "aeolian" which appears to have been either a pianola or a player-piano made by the Aeolian Co. of America. Heaviside evidently could play the piano and once taught himself Beethoven's Opus 90. He was especially fond of the "divine Schubert" and probably possessed rolls of Schubert's music for playing the "aeolian" mechanically. This is not as gruesome as it sounds: apparently the nearest modern equivalent is a set of hi-fi equipment, as the Aeolian Company took pride in the fact that its player-pianos were excellent instruments in themselves.

The quality of Heaviside's life as he neared his death left a great deal to be desired. For more than a year (August 1921–October 1922) he had no gas for heat or light. He was very poor and not the best housekeeper. He owed much to the voluntary efforts of the local "bobby" as he called him, P. C. Brock, and to Brock's small daughter. But despite his own troubles he could still take an interest in the problems of the world at large and his scientific correspondence was enlivened by references to passing events with frequent quotations or impromptu verses. The United States' claim for the repayment of the English debt in 1923 led to some scathing remarks on American greed and greed in general ending with:

> "Eat slowly. Only men in rags or gluttons deep in sin mistake themselves for carpet bags and shove the vittles in."[3]

Heaviside did meet with much opposition to his work and ideas, but in later life, starting in 1891 with his election to the Royal Society, he received fairly widespread recognition. However it should be remembered that he was never in paid employment after the age of 24 and this resulted in some financial problems.

Many friends were aware of this and tried to help. The first official attempt to give him some financial support came from the Royal Society via some friends (G. F. Fitzgerald, Sir Oliver Lodge and John Perry). But he refused the offer of an honorarium. This was early in 1894. In 1896 he was granted a Civil List pension of £120 p.a. by the Government. (This was apparently on account of the efforts of the same three men together with the help of Lord Rayleigh and Lord Kelvin. Sir Oliver Lodge was a personal friend of A. J. Balfour, then Leader of the House of Commons and a man with scientific interests. Balfour's uncle, Lord Salisbury, was Prime Minister and Lord Rayleigh was Balfour's brother-in-law.) This pension was increased by a further £100 p.a. in 1914. Heaviside also had a small income from his writings and occasionally he would receive cash from well-wishers. However, he was extremely touchy about charity and would not see his friend Searle for a period of many months towards the end of his life because of his anger about a financial matter.

In a short presentation it is possible to give only the briefest outline of the life and work of Oliver Heaviside. It is hoped that a balanced picture has been presented whilst at the same time showing Heaviside to be the truly interesting man that he was. Undoubtedly a genius, he was also a philanthropist in his own, unique way. He once wrote an (unpublished) article on the immortality of the soul:

> "... There are large souls and small souls. The immortal soul of the scienticulist is a small affair, scarcely visible. Indeed its existence has been doubted. That of a Shakespear or a Newton is stupendously big. Such men live the best parts of

their lives after they are dead. Maxwell is one of these men. His soul will live and grow for long to come, and hundreds of years hence will shine as one of the brightest stars of the past, whose light takes ages to reach us."

References

1. Mercer, D. M. A., "Rewards that Came too Late," BBC Broadcast on January 22nd and March 2nd, 1976..
2. Appleyard, R., "Pioneers of Electrical Communication," Macmillan & Co., 1930: *Reprinted* 1968, Books for Libraries Press, N.Y.
3. Whittaker, E. T., *Bulletin Calcutta Mathematical Society*, 1928–9, **20**, 199–220: *Reprinted* as Foreword in Chelsea reprint of reference 6.
4. Josephs, H. J., "The Heaviside Papers found at Paignton in 1957," *Proc. IEE, Part C*, March 1959, 70–76: *Reprinted* as Appendix to Vol. 3 in Chelsea reprint of reference 6.
5. Heaviside, O., "Electrical Papers," (2 vols.), Macmillan, 1892.
6. Heaviside, O., "Electromagnetic Theory," (3 vols.), The Electrician Printing and Publishing Co., 1893, 1899 and 1912. *Reprinted* by photolitho, E. & F. N. Spon Ltd., London, 1951 (with a critical and historical introduction by E. Weber). *Reprinted*, Chelsea Publishing Co., New York, 1971 (with a Foreword by Sir Edmund Whittaker – reprint of reference 3; also Appendix to Vol. 1 "The Work of Oliver Heaviside," B. A. Behrend – reprinted from *The Electrical Journal*, January and February 1928, Pittsburgh; and Appendices to Vol. 3 "Some Unpublished Notes of Oliver Heaviside," H. J. Josephs, – reprinted from reference 7, and "The Heaviside Papers found at Paignton in 1957," H. J. Josephs – reprint of reference 4).
7. "The Heaviside Centenary Volume," IEE, 1950. (Contains addresses made at the Heaviside Centenary Meeting, the 1078th ordinary meeting of the IEE, 18th May, 1950, together with a number of papers dedicated to the work and memory of Oliver Heaviside. Approximately 100 pages – a wealth of information and some pictures.)
8. Pupin, M. I., "Wave Transmission over Non-Uniform Cables and Long-Distance Air-Lines," *Trans. AIEE*, 1900, **XVII**, 445–512.

Bibliography

Berg, E. J., "Heaviside's Operational Calculus," McGraw Hill, 2nd edition, 1936. (Includes brief personal sketch, pp. xiii–xv.)

Josephs, H. J., "Heaviside's Electric Circuit Theory," Methuen, 1946.

The Electrical World, January-June 1925, **85**. (Includes a variety of articles: p. 337; p. 364;
pp. 403–405, by Sir Oliver Lodge;
pp. 405–407, by B. A. Behrend;
p. 475, by Prof. E. J. Berg;
p. 513, a letter from J. R. Carson.)

Piaggio, H. T. H., "The Operational Calculus," *Nature*, 1943, **152**, 93.

Appleyard, R., "Dictionary of National Biography."

Fitzgerald, G. F., "Heaviside's Electrical Papers," *in* "The Scientific Writings of the Late Geo. Francis Fitzgerald," Longmans Green, 1902, pp. 292–300.

The author obtained his BSc in Theoretical Mechanics from the University of Nottingham in 1968. He obtained his PGCE from Keswick Hall Teachers' Training College, Norfolk, and spent 1 year (on VSO) teaching mathematics in Kenya. He subsequently obtained his MPhil (in Electrical Engineering) from the University of Nottingham. He has held a variety of teaching appointments at places including Gresham's School, Paisley College of Technology and Norwich School. Since August 1981 he has been Head of the Mathematics Department at the Mary Erskine School in Edinburgh.

Solutions to Calculator Challenges

The Challenges were published in Volume 1, Number 3, p. 100.

11. 3 was displayed as 7.
The actual calculations were

$$5632 + 7343 = 12975$$

$$239 \times 367 = 87713.$$

12. Tsu Ch'ung-Chih:

$$\frac{355}{113} = 3.1415929\ldots.$$

13. An example of ill-conditioned equations. Did you think your calculator was on the blink?

$$x_1 = 1776 \qquad y_1 = -4186$$

$$x_2 = -770 \qquad y_2 = 1816.$$

Thought of as the equations of straight lines it will be seen that their gradients are very nearly equal:

$$-2.3585 \text{ and } -2.3581 \text{ to 4 d.p.}$$

Thus the slightest change of the gradient of one line, and the point of intersection of the two lines changes radically.