

COMMENTARY

Faraday and the *Philosophical Magazine*

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Faraday is considered to be one of the greatest scientists of all time. He not only was a meticulous experimentalist, a true experimental wizard, but also a very prolific author. The many important contributions (almost 50) that he published in the *Philosophical Magazine* make it highly desirable to catalogue his various inventions, ‘discoveries’ in his own words, in a scientific language so characteristic of the nineteenth century. It is the purpose of this commentary to guide the reader through his achievements in electrochemistry, magnetism, electric and electromagnetic induction, even ‘industrial’ applications; to enable him to address a present day audience by means of his contributions to the *Philosophical Magazine*.

Keywords: electrical conduction; electrical conductivity; electrical properties; electromagnetic; magnetism; magnetic transitions; magnetic properties; history of science

1. Introduction

Probably no other discovery made in the nineteenth century permanently transformed society more than that of electricity. The discovery itself was not a sudden one, but covers a period of about 90 years, namely from Luigi Galvani’s (1737–1798) first observation of ‘bioelectricity’ in 1771 and Alessandro Volta’s (1745–1827) first electric battery around 1800 to James Clerk Maxwell’s (1831–1879) famous equations. Nowadays life without electricity seems inconceivable: modern societies depend crucially on a stable supply of electricity; any local or nation-wide blackout causes severe disruptions in the daily and public life of many.

Most likely – perhaps with the exception of Maxwell – the biggest contribution to research in electric phenomena was made by Michael Faraday (1791–1867), who according to the testimony of contemporary scientists [1] must have been an exceptional experimental wizard. Faraday not only was a meticulous experimentalist, but also a prolific author as can easily be judged from his almost 50 contributions to the *Philosophical Magazine*, the title page of his 1833 paper there being depicted is shown in Figure 1.

There are quite a few biographies of Faraday available and essays or publications on certain aspects of his life or phenomena discovered by him. This commentary is meant to let Faraday speak with his own words, to explain his figures in his way,

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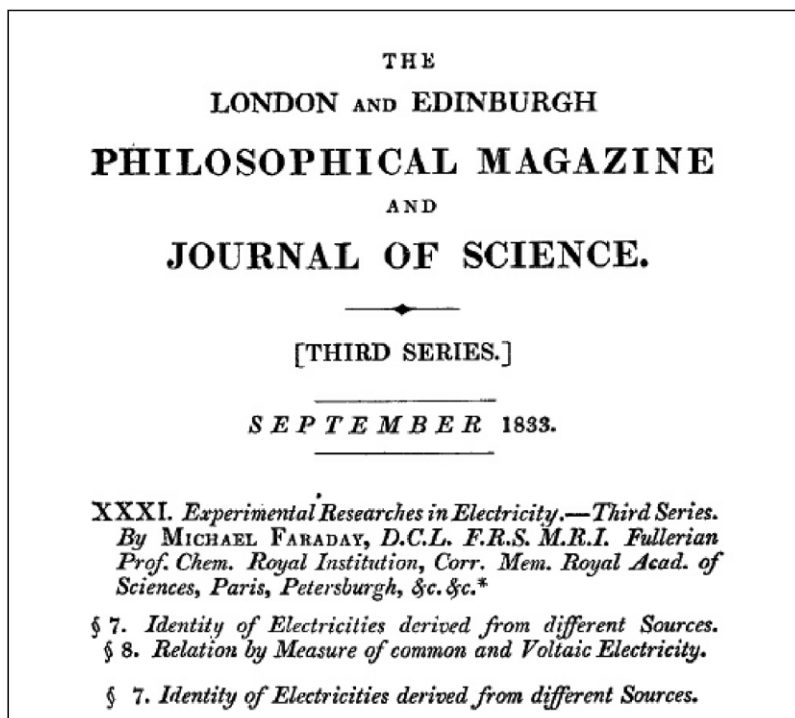


Figure 1. Title page of Faraday's 1833 contribution to the *Philosophical Magazine* [4].

to lead back to the nineteenth century, into a time in which such figures had to be prepared as etchings, i.e. were a piece of art.

It is important to emphasize that, in the following, reference is made solely to Faraday's publications in the *Philosophical Magazine*. For a more complete account of all of his achievements, see, for example, Ref. [2].

2. Faraday and electrochemistry

In scanning through his papers, see Table 1, it is obvious that he persistently used the same title for one and the same research topic. His series of publications entitled *Experimental researches in electricity*, carried out over a period of 13 years, was mostly devoted to electrochemical problems. His aim was to have a reproducible, stable, 'efficient source of electricity', which in the 1830s and 1840s was a 'galvanic cell' or electric battery as it is called nowadays. For this purpose he varied nearly everything that can be varied: the shape of the cell itself, the type of electrodes, the distance between the electrodes, and the electrolyte. He worried about the production of gases on the surfaces of the electrodes and speculated about the type of electric transport that occurred. And each variation was described carefully in relation to all the other parameters he thought would perhaps determine the output of electricity.

The Cu/Zn battery, described in [12], see also Figure 2, very soon became a standard device for investigations of ‘electricity’. In order to appreciate Faraday’s electrochemical experiments, one has to imagine that the shell of a battery was usually made from wood, most likely closing the joints with pitch. Particular types of electrolytes – he experimented with all sorts of acids – must have caused severe damage to the body of such a cell. It seems that already by 1835 Faraday had a very good idea about the kind of electric transport occurring in a galvanic cell which, by the way, does not differ very much from present day descriptions.

From this it seems apparent that the peculiar character and condition of an electrolyte is essential in one part of the voltaic circuit; and its nature being considered, good reasons appeal why it and it alone should be effectual. An electrolyte is always a compound body; it can conduct, but only whilst decomposing. Its conduction depends upon its decomposition and the transmission of its particles in directions parallel to the current; and so intimate is this connexion, that if their transition be stopped, the current is stopped also; if their course be changed, its course and direction changes with them; if they proceed in one direction, it has no power to proceed in any other than a direction invariably dependent on them. [8]

3. Faraday and magnetism

3.1. Ferromagnetism

Around 1835 Faraday also got interested in magnetic studies and, very typically for him, immediately started to vary parameters experimentally. How difficult and sometimes misleading ‘low temperature’ studies were at that time can be gathered from a paper [13] that appeared in 1836:

General views have long since led me to an opinion, which is probably also entertained by others, though I do not remember to have met with it, that all the metals are magnetic in the same manner as iron, though not at common temperatures or under ordinary circumstances . . .

I took occasion during the very cold weather of December last, to make some experiments on this point. Pieces of various metals in their pure state were supported at the ends of fine platinum wires, and then cooled to a very low temperature by the evaporation of sulphuric acid . . . and the magnetic state (was) judged by the absence or presence of (magnetic) attractive forces . . .

Cobalt and Chromium are said to be both magnetic metals. I cannot find that either of them is so, in its pure state, at any temperature. [13]

Almost ten years later, in 1845, he performed similar experiments at high temperatures:

It was to me a point of great interest to ascertain whether, and at what temperature, cobalt would lose this power and become as the unmagnetic metals. To my surprise I found this to be very high, not merely much higher than with nickel, but far above that required for iron or steel, and nearly approaching the temperature of melted copper. That for iron is a moderate red heat, and that for nickel the temperature of boiling oil only. As the temperature rises, the magnetic force of the cobalt continues, apparently undiminished, to a certain degree of heat, and then suddenly ceases; and it comes on as suddenly in descending from still higher temperatures. [28]

And came to the remarkable conclusion that

. . . it appears that only iron, nickel and cobalt are magnetic, or can be made magnetic amongst metals . . . and that it is only a difference of temperature which distinguishes

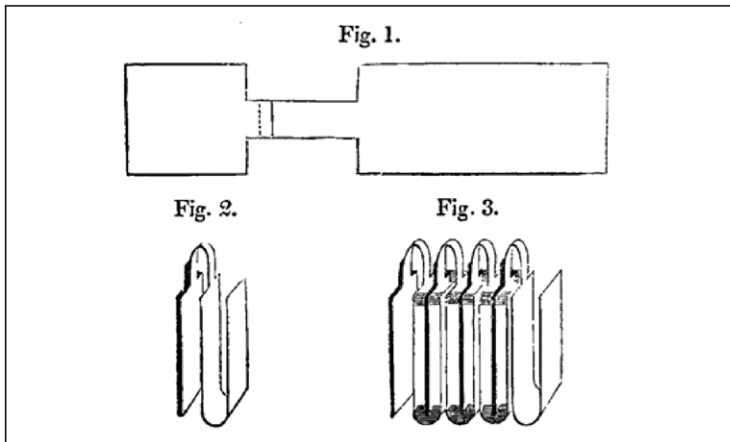


Figure 2. My zinc plates were cut from rolled metal, and when soldered to the copper plates had the form delineated, fig. 1. These were then bent over a gauge into the form fig. 2, and when packed in the wooden box constructed to receive them, were arranged as in fig. 3, little plucks of cork being used to keep the zincplates from touching the copper plates, and a single or double thickness of cartridge paper being interposted between the contiguous surfaces of copper to prevent them from coming in contact. [12].

these three from the rest, just as it also in a similar respect distinguishes them from each other. [28]

One has to admit that Faraday gained very good insight from his experiments of the temperature dependence of magnetism. Of course, he was not aware of some of the rare earth elements, since they were discovered only quite a few years later. And he could not measure the actual temperature at which Fe or Co become non-magnetic, a temperature that in the twentieth century eventually would be called the Curie temperature.

In his obituary on Faraday in the *Philosophical Magazine* (1867) de la Rive [1] wrote: ‘In 1831 Faraday discovered electrical induction; it is the most important, although perhaps not the most brilliant of his discoveries’. It seems that almost 150 years later his statement is still valid, in particular if one recalls Faraday’s ‘lines of magnetic force’, which eventually lead to Maxwell’s famous equations.

Faraday was very careful with all his statements. Whatever he could not prove experimentally he usually formulated as a question, indicating thus that it was just a speculation. In particular, in his papers *On some points of magnetic philosophy* [42] and *Magnetic remarks* [43] he distinguished meticulously between ‘facts’ and ‘speculation’. For this very reason he rigorously and publically opposed any kind of occultism such as mesmerism or table-turning which was very popular at his time. It should be noted that his figure 2 in [38], reproduced in Figure 3, is probably the universally most well-known image of magnetism, see also Figure 4.

3.2. Diamagnetism

Intrigued by results obtained by Zantedeschi¹ [50], in 1847 Faraday performed a series of experiments in which he could conclude that most materials

are diamagnetic.² Using the following set-up

... The two terminal pieces of iron (of the electro-magnet) forming the virtual magnetic poles were each 1.7 inch square and six inches long; but the ends were shaped to a form approaching that of a cone... The apex of each end was rounded... When these terminations are brought near to each other, they give a powerful effect in the magnetic field, and the axial line of magnetic force is of course horizontal, and on a level nearly with the upper surface of the bars. [35]

he could show that

When the flame of a wax taper was held near the axial line, but on one side or the other, about one-third of the flame rising above the level of the upper surface of the poles, as soon as the magnetic force was on, the flame was affected; and receded from the axial line, moving equatorially, until it took an inclined position, as if a gentle wind was causing its deflection from the upright position; an effect which ceased the instant the magnetism was removed. [35]

Very typically of his approach to newly discovered phenomena, he immediately tried to change parameters. First of all he made sure that no electric effect was present. Then he changed the temperature of the flame and eventually added various gases to it. In doing so he found out that, for example, nitrogen or hydrogen are diamagnetic, while oxygen seemed to be magnetic. The ‘true zero’ between ‘bodies as being magnetic or diamagnetic in relation to each other’ he assumed to be vacuum. [35]

Faraday constantly worried about possible implications of diamagnetism and, in particular, about the ‘force’ exerted by a permanent magnet. In his paper *On some points of magnetic philosophy* [42], for example, he once again came back to these two issues.

4. Faraday and electromagnetic induction

4.1. Electric induction

In 1836 Michael Faraday observed *inter alia* that the charge on a charged conductor resided only on its exterior and had no influence on anything enclosed within. To demonstrate this fact, he built a room coated with metal foil and allowed high-voltage discharges from an electrostatic generator to strike the outside of the room. He used an electroscope to show that there was no electric charge present on the inside of the room’s walls. However, the so-called Faraday cage, as this kind of set-up is now called, was not the only induction experiment he performed. For example, he performed the following electric induction³ experiment with which he (again) tried to persuade the scientific audience that induction leads to charged objects with the charge located at the surface, see also Figure 5.

4.2. Electromagnetic induction

For his right to claim to be the true inventor of electromagnetic induction⁴ (1831) Faraday had to contend with two Italian physicists, namely Leopoldo Nobili (1784–1835) and Vincenzo Antinori (1792–1865), who claimed in 1832 in a publication in the *Annales de Chimie et de Physique* not only priority rights but

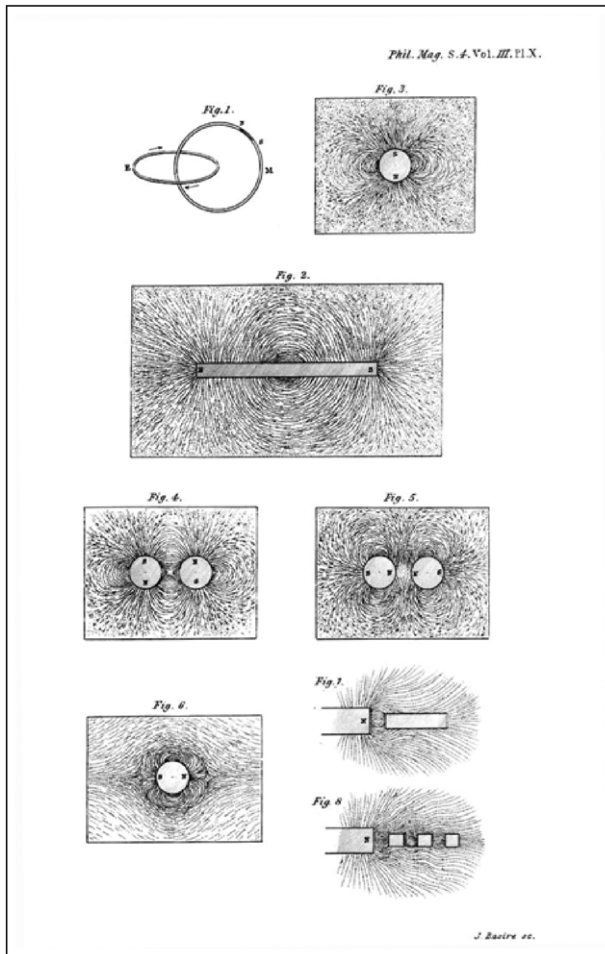


Figure 3. (fig. 1): If a current of electricity be sent round the ring *E* in the direction marked, then lines of magnetic force will be produced, correspondent to the polarity indicated by a supposed magnetic needle placed at *NS*, or in any other part of the ring *M* to which such a needle may be supposed to be shifted.

(figs. 2–5): The physical lines of force, in passing out of the magnet into space, present a great variety of conditions as to form. At times their refraction is very sudden, leaving the magnet at right, or obtuse, or acute angles, as in the case of a hard well-charged bar-magnet, fig. 2; in other cases the change of form of the line in passing from the magnet into space is more gradual, as in the circular plate or globe-magnet, figs. 3, 4, 5.

(fig. 6): Though the physical lines of force of a magnet may, and must be considered as extending to infinite distance around it as long as the magnet is absolutely alone, yet they may be condensed and compressed into a very small local space, by the influence of other systems of magnetic power. This is indicated by fig. 6.

(figs. 7–8): If we take a large bar-magnet, and place a piece of soft iron, about half the width of the magnet, and three or four times as long as it is wide, end on to, and about its own width from one pole, and covering that with paper, then observe the forms of the lines of force by iron-filings; it will be seen how beautifully those issuing from the magnet converge, by fine inflections, on to the iron, entering by a comparatively small surface, and how they pass out in far more diffuse streams by a much larger surface at the further part of the bar, fig. 7. If we take several pieces of iron, cubes for instance, then the lines of force, which are altogether outside of them, may be seen undergoing successive undulations in contrary directions, fig. 8. [38].

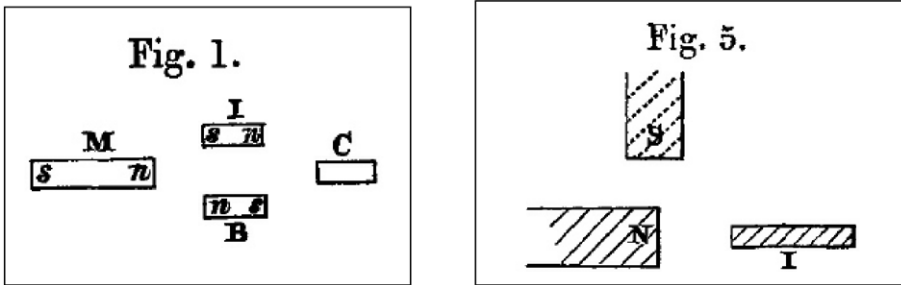


Figure 4. If an ordinary magnet *M*, Fig. 1, acting upon a piece of iron or other para-magnetic matter *I*, renders it polar by throwing its near end into the contrary or *S* state in the manner usually understood, and, acting upon a like piece of diamagnetic matter as bismuth *B*, renders it also polar, but with the near end in the same state; then *B* and *I* are for the time two magnets, and must act back upon the magnet *M*; or if they could be made able to retain their states after *M* is removed (and that is the ease with *I*), would act as magnets upon a third piece of magnetic matter as *C*. [42].

When the *N* pole of a magnet (Fig. 5) is acting in free space, its force is sensible around to a certain amount when a piece of soft iron, *I*, is brought near it much of its force gathers up upon that iron, but the whole amount of force from and about the *N* pole is the same; when an *S* pole is brought up, either of another magnet or of itself (for the effect is precisely the same), much of the force exerted upon the iron is removed from it, and falls upon the *S* pole, but the amount of force about the pole *N* remains the same; all of which can be proved experimentally by a helix on the soft iron and loops carried over the *N* pole. [42].

also doubted the correctness of his experimental results. This quarrel must have dragged on for a few years, since in 1840 Faraday wrote an open letter [21] to (Joseph Louis) Gay-Lussac, the editor of the *Annales*:

MY DEAR SIR,

I BEG to address to you the following pages upon the subject of electro-magnetism, and request the favour of their insertion in the *Annales de Chimie et de Physique*. They may, I fear, provoke a controversy that I would willingly avoid; but under the existing circumstances I feel compelled to adopt the present course of proceeding, for silence, should I maintain it, would be regarded as an admission of error, not only in a philosophical, but also in a moral point of view from which I believe myself wholly exempt...

You will undoubtedly understand that I allude to the Memoir by Messrs. Nobili and Antinori... [21]

... I showed in my first memoir, that when a piece of metal is passed either before a single pole, or between the two opposite poles of a magnet, or near electromagnetic poles, whether ferruginous or not, electric currents are produced across the metal transverse to the direction of motion. This fact is proved by means of wires, plates and discs; and in all these cases the electric current was in the same direction, whether the metal were brought near to, or caused to recede from the magnet, provided that the direction of its movements were unaltered. [21]

This letter, which actually appeared in two parts, namely as Refs. [21] and [22], is particularly interesting, since it contains a summary of Faraday's findings in terms of a series of 12 figures engraved on a single plate picking the example of a rotating

metal disc (rotation direction R), see Figure 6. In these figures he depicts various situations of having a permanent magnet with either one or both magnetic poles in the vicinity of the rotating disc and shows the directions of the measured currents. It is the direction of the currents, indicated carefully by arrows, in which he differs from the interpretations of Nobili and Antinori, since they claim their directions to be opposite to the ones he found.

Faraday ends this letter, which beautifully explains in simple terms the effect of electromagnetic induction, by expressing again his anger:

I cannot conclude this letter without again expressing my regret at having been obliged to write it; but if it be recollected that Messrs. Nobili and Antenori's memoirs were written and published after my original memoirs; that their last paper appeared even in the Annales de Chimie et de Physique after mine; and that it had consequently the appearance of advancing the science further than I had done; that both papers accuse me of error in experiment and theory, and also of dishonesty... [22]

Since it turned out that electromagnetic induction was discovered more or less independently also by Joseph Henry (1797–1878) [51,52] this effect is nowadays attributed to both Faraday and Henry. Incidentally, Henry's 1841 article [51] in the *Philosophical Magazine* extends over 32 printed pages.

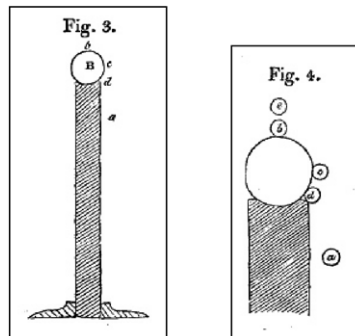


Figure 5. A cylinder of solid shell-lac, 0.9 of an inch in diameter and seven inches in length, was fixed upright in a wooden foot (fig. 3.): it was made concave or cupped at its upper extremity so that a brass ball or other small arrangement could stand upon it. The upper half of the stem having been excited negatively by friction with warm flannel, a brass ball, B, 1 inch in diameter, was placed on the top, and then the whole arrangement examined by the carrier ball and Coulomb's electrometer... [16].

To suppose that the upper part of the uninsulated ball B, should in some way be retained in an electrified state by that portion of the surface which is in sight of the shell-lac, would be in opposition to what we know already of the subject. Electricity is retained upon the surface of conductors only by induction; and though some persons may not be prepared as yet to admit this with respect to insulated conductors, all will as regards uninsulated conductors like the ball B; and to decide the matter we have only to place the carrier ball at e (fig. 4.), so that it shall not come in contact with B, uninsulate it by a metallic rod descending perpendicularly, insulate it, remove it, and examine its state: it will be found charged with the same kind of electricity as, and even to a higher degree than, if it had been in contact with the summit of B. [16].

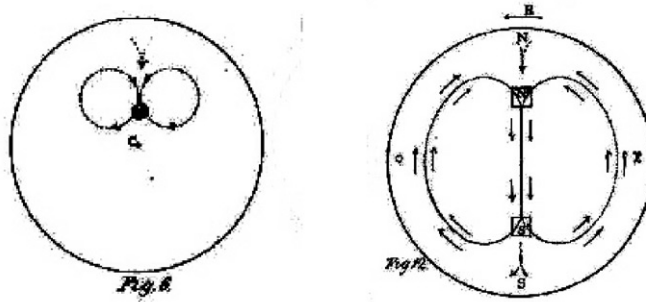


Figure 6. If figure 12 be examined, it will be instantly seen that it results in the most simple manner from the action of the two poles. Thus, as far as the upper or north pole only is concerned, the currents are as in figure 6. But as with the north pole, the current determined by it moves from the circumference towards the centre, so with the south pole, in the same or corresponding position, the currents move from the centre to the circumference; and consequently in fig. 12 they are continued along the diameter *N, S*, through the centre of the plate, to return in the direction of the arrows upon the sides *E, O*. The points upon which I find my views to disagree with the indications of the galvanometer obtained by Messrs Nobili and Antenori are, first, the direction of the currents at *N* and *S*, which is contrary to what I obtained; and, secondly, the existence of any oblique axis of power. [22].

5. Faraday and technology

After a first unsuccessful attempt in 1855, a really revolutionary ‘industrial’ project was completed,⁵ namely a transatlantic telegraph cable connecting the United Kingdom with the United States of America. Unfortunately, there were quite a few technical problems connected with this enterprise, since already very soon the signal quality started to decrease thus causing slow speeds of transmission. Only in a second attempt, a few years later, did the telegraph connection to the United States turn out to work properly. Clearly enough, this project raised quite some scientific curiosity [39,53–55]. Airy, the Astronomer Royal, worried for example about ‘*the mechanical conditions of the deposit of a submarine cable*’ [53]. Already on account of the first attempt Faraday commented [39] on the technical difficulties met:

Now it is evident that the subterraneous wire with its insulating covering may be assimilated exactly to an immense Leyden battery:⁶ the glass of the jars represents the gutta percha; the internal coating is the surface of the copper wire; the external surface is the moistened earth. [39]

The use of gutta percha⁷ seems to have been Faraday’s idea, since in a letter [36] to the *Philosophical Magazine* from 1848 he states:

I have found gutta percha very useful in electrical experiments . . . Its use depends upon the high insulating power which it possesses und ordinary conditions . . . [36]

The letter ends very nicely with the sentence:

All I desire in this note is to make known its use in the arrangement of extemporary or permanent electrical apparatus for the advantage of working philosophers, both juvenile and adult. [36]

6. Résumé

Perhaps the last sentence best summarizes Faraday's personality. Although having become world-famous he refused to accept traditional signs of recognition. He never forgot that he had started out as an apprentice in a bookbinder's shop, as a late-comer in science: he rejected a knighthood and refused to become President of the Royal Society. Faraday's scientific output, a considerable amount thereof is to be found in the Archives of the *Philosophical Magazine*, not only influenced scientists of his time, such as Maxwell and others, but also generations to come. Einstein is said to have kept a picture of him in his study together with Newton and Maxwell.

There are quite a few more of his experiments that ought to be mentioned such as his attempts to prove the connection between light and magnetism [29,30] which in a way anticipated the Zeeman effect [56,57]. In here only his publications in the *Philosophical Magazine* were taken into account, since the archives of this journal can easily be accessed on-line and thus ought to be of interest also for a general audience.

It became customary to name quite a few effects or properties after him: the *Faraday law of induction*, the *Faraday cage*, or the *Faraday constant*, to name only a few. The broad spectrum of his scientific interests and his theoretical ideas well ahead of Maxwell's equations is indeed outstanding and deserves to be read in its original form.

Notes

1. Francesco Zantedeschi (1797–1873), http://en.wikipedia.org/wiki/Francesco_Zantedeschi
2. Diamagnetic materials produce a magnetic field in the opposite direction of that of an applied external magnetic field.
3. The electromotive force ε is given by

$$\varepsilon = -\frac{d\Phi_B}{dt},$$

where Φ_B is the magnetic flux and t the time.

4. The Maxwell–Faraday equation (Faraday's law of induction) is of the form

$$\nabla \times E = -\frac{\partial B}{\partial t},$$

where E is the electric field, B the magnetic field, and t the time.

5. By the way, the very first telegram was sent by Queen Victoria to the President of the United States, James Buchanan.
6. Leyden battery or Leyden jar, see http://en.wikipedia.org/wiki/Leyden_jar.
7. See <http://en.wikipedia.org/wiki/Gutta-percha>

Table 1. Faraday's contribution to the *Philosophical Magazine*.

Title	Year	Reference
Experimental researches in electricity	1833	[4,5]
	1834	[6]
	1835	[8–11]
	1836	[12]
	1838	[15–17]
	1839	[18,19]
	1846	[31–33]
	1850	[37]
On the chemical and contact theories of the voltaic battery	1843	[25]
On the magnetic relations and characters of the metals	1836	[13]
	1845	[28]
	1835	[7]
On the magneto-electric spark and shock, and on a peculiar condition of electric and magneto-electric induction		
On magnetoelectric induction	1840	[21,22]
On static electrical inductive action	1843	[24]
On the magnetic affection of light, and on the distinction between the ferromagnetic and diamagnetic conditions of matter	1846	[29,30]
On the physical character of the lines of magnetic force	1852	[38]
On electric induction – Associated cases of current and static effects	1854	[40]
On electro-dynamic induction in liquids	1854	[41]
Account of an experiment in which chemical decomposition has been effected by the induced magneto-electric current	1832	[3]
On some supposed forms of lightning	1841	[23]
A speculation touching electric conduction and the nature of matter	1844	[27]
Thoughts on ray-vibrations	1846	[34]
On the diamagnetic conditions of flame and gases	1847	[35]
On the use of gutta percha in electrical insulation	1848	[36]
On subterraneous electro-telegraph wires	1854	[39]
On some points of magnetic philosophy	1855	[42]
Magnetic remarks	1855	[43]
On electric conduction	1855	[44]
Further observations on associated cases in electric induction, of current and static effects	1855	[45]
On the action of non-conducting bodies in electric induction	1856	[46]
On the conservation of force	1857	[47]
Experimental relations of gold to light	1857	[48]
On regelation, and on the conservation of force	1859	[49]
Note from Professor Faraday on the preceding paper	1837	[14]
An answer to Dr. Hare's letter on certain theoretical opinions	1840	[20]
On Dr. Hare's second letter, and on the chemical and contact theories of the voltaic battery	1843	[26]

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