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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

On the Changes Produced by Magnetisation in the Dimensions of Rings and Rods of Iron and of Some Other Metals

Shelford Bidwell

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VII. *On the Changes produced by Magnetisation in the Dimensions of Rings and Rods of Iron and of some other Metals.*

By Shelford Bidwell, *M.A., F.R.S.*

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In a paper communicated to the Royal Society in 1885* I described some effects of magnetisation upon the dimensions of iron rods. It was there shown that the elongation which such a rod at first undergoes when magnetised (a phenomenon which had been carefully studied by Joule and others) does not, as had been believed, remain unchanged at a maximum when the magnetising force exceeds that which is sufficient to produce so-called saturation. On the contrary, it is found that, when the magnetising force is continually increased beyond this limit, the elongation becomes gradually less until the rod is at last actually shorter than it was in the unmagnetised condition.

Though there could be little doubt as to the general qualitative reality of the effects described, the experimental evidence was nevertheless not free from certain defects which I was not at the time able to overcome.

In order to obtain a magnetic field of the highest intensity possible with a limited battery power, a solenoid was used which was not much longer than the rods themselves, and the field, therefore, was not quite uniform. The effect of the ends of the rods was also uncertain, and might have played some material part in the production of the phenomena in question. Another serious element of uncertainty arose from the fact that the rods with which the experiments were made were permanently magnetised. Since it was impossible to remove a rod from the instrument and demagnetise it before every one of a series of observations, it was thought desirable that the amount of residual magnetism which it contained should at least be the same throughout the series. This object was attained by passing through the coil at the beginning of an experiment a current equal to the strongest which it was intended to use subsequently, the permanent magnetism thus imparted to the iron having been found to be quite unaffected by the passage through the coil of currents weaker or not stronger than the first. The effect of this residual magnetism upon the elongations and retractions was not easily ascertainable. Lastly, the magnetisation might with advantage have been carried considerably further if sufficient battery power had been available.

* 'Roy. Soc. Proc.,' vol. 40, 1886, p. 110.

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It is clear that if such experiments could be made with iron rings instead of rods several of these objections would at once disappear. The field due to a current through a wire wrapped evenly round the ring would be very approximately uniform and easily calculable, while the ends, with their attendant disadvantages and uncertainties, would no longer exist. I have from time to time during the last two years made attempts in this direction, but the practical difficulties encountered turned out to be unexpectedly great, and it is only recently that I have succeeded in surmounting them.

To bring the strong fields required within the compass of a battery of reasonable size, it was essential that the rings should be small. On the other hand, if they were too small, the exceedingly minute changes in their diameters due to magnetisation would not be measurable. Ten centimetres had been fixed upon for the length of the rods used in the old experiments, as being the shortest which was advantageously possible; but a ring 10 cm. in diameter would require more than three times the number of turns of wire necessary for the rods to give an equal field, and the increased resistance thus introduced would demand a correspondingly larger battery. It was finally determined to give the rings a mean diameter of 6 cm., but with this small diameter the number of turns of wire per centimetre which could be properly wound on was less than in the case of the straight solenoid. The strongest field yet obtained with such a ring, using a battery of 30 GROVE's cells, was 450 C.G.S. units. When the same battery is employed with the straight solenoid the strength of the field at the centre reaches 840 units.

Again, the troublesome and misleading effects of heat are much less easily avoided in a ring than in a straight rod. The importance of securing a steady temperature may be inferred from the fact that, taking the coefficient of expansion of iron to be 0·0000122, the elongation accompanying a rise of temperature of a single degree is more than eighty times greater than that which it is desired to measure. Several rings were prepared before the difficulty was surmounted of sufficiently protecting the iron from the heat generated in the surrounding coil by strong currents. Unless an interval of at least half a second intervenes between the closing of the circuit and the commencement of the consequent heat expansion, no satisfactory observation can be made.

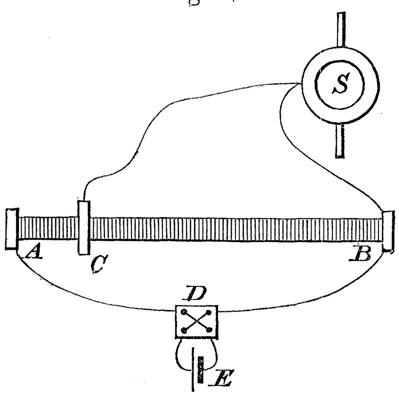
In order to get rid of the permanent magnetism which remains after every observation, a modification was adopted of the device employed by Professor EWING, and described by him in 'Phil. Trans.,' vol. 176, p. 537. For the variable resistance it was found advantageous to use a long German silver wire, wound in a close spiral upon a wooden cylinder, instead of a tube containing sulphate of zinc solution. Contact with the wire was made by a transverse spring which was capable of sliding from end to end of the cylinder. The arrangement is indicated in fig. 1. It will be seen that the German silver spiral AB acts to the coil wound upon the ring S as a shunt, the resistance of which gradually diminishes from 26 ohms* to nothing as the

* The resistance of the whole spiral.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

spring C slides from A to B. While the spring is so moving the current from the battery E is being rapidly reversed by the commutator D: thus, the coil upon the ring is traversed by a series of alternating currents of decreasing strength, the effect of which is to completely demagnetise the ring. In practice the slide and the commutator were operated together by simply turning a handle.*

Fig. 1.



Passing over the earlier and altogether unsuccessful attempts in which the insulated wire was wound directly upon the iron, I give below particulars of three rings which yielded results of value, and which will be distinguished as No. 0, No. 1, and No. 2. The first was of use only for comparatively weak currents; the second and third could, with a little care, be employed in connection with 30 GROVE's cells.

Ring No. 0.—This was made of soft iron rod of a superior quality, commercially known as "bright rod." The joint was carefully welded and the ring was turned in the lathe to a circular section. It was then covered with four layers of flannel, cut into strips and wound with three coils of insulated wire.

External diameter of ring	6·50 cm.
Mean diameter	5·85 cm.
Diameter of section	0·515 cm.
Diameter of copper wire	0·07 cm.
Total number of turns	450
Field† due to coil	30 × C nearly.

C being the current expressed in ampères.

Two brass rods, 6 cm. and 8 cm. in length, were attached by clamps to the exterior of the coils, forming prolongations of a diameter of the ring. These rods served to communicate the variations in the diameter of the ring to the measuring instrument, which will be described further on.

* The iron was, of course, demagnetised without being removed from the instrument, the slide apparatus being connected when required by means of a switch.

† The field at a distance r from the axis of the ring $= 2ni/r$, where n is the number of turns of wire and i the current in C.G.S. units.

Ring No. 1.—This was made from a piece of the same rod as the last. The joint was welded and the whole ring was filed smooth, but it was not turned. The ring was covered with a boxwood case of circular section (something like a WINTER's ring), which was formed of two rings of semicircular section, having grooves of semicircular section cut upon their flat sides. The grooves in the two portions of the boxwood ring enclosed a space slightly larger than was necessary for the reception of the iron ring, allowing a play of about 1 mm. Five layers of copper wire were wound over the boxwood ring.

External diameter of iron ring	6·7 cm.
Mean diameter	6 cm.
Diameter of section	0·7 cm.
Diameter of section of boxwood ring	1·8 cm.
Diameter of copper wire	0·07 cm.
Total number of turns	644
Field due to coil	42·9 × C.

Brass rods were screwed into small holes drilled at opposite ends of a diameter of the iron ring and passed freely through the boxwood casing and the coils, pieces of india-rubber tubing being inserted between the rods and the wires of the coils.

Ring No. 2 was a welded ring made from a different specimen of iron. It was, like No. 0, turned to a circular section, and was remarkable for the extreme facility with which it could be cut in the lathe. Rods of iron (instead of brass) were screwed into two opposite holes, and care was taken to make the screws fit very tightly, with the object of securing nearly perfect magnetic uniformity throughout the ring. This ring was, like No. 1, covered with a wooden case of circular section, but the holes made in the wood to admit the rods were furnished with short spouts of glass tubing, having an external diameter of 0·57 cm. and projecting about 2·5 cm.; the rods were turned down to such a size as to pass freely through the tubes. The wire with which the wooden ring was covered was wound in six layers closely up to the tubes, and the break in the uniformity of the coil was very slight. The tubes also served to shield the rods from the heat radiated by the coil when a current was passing.

External diameter of iron ring	6·70 cm.
Mean diameter	6·03 cm.
Diameter of section	0·67 cm.
Diameter of section of wood casing	1·3 cm.
Diameter of copper wire	0·07 cm.
Total number of turns	869
Field due to coil	57·6 × C

Some experiments were also made with two iron rods.

Rod No. 1.—Commercial iron wire:—

Length	10 cm.
Diameter	0·27 cm.

Rod No. 2.—Soft charcoal iron:—

Length	10 cm.
Diameter	0·33 cm.

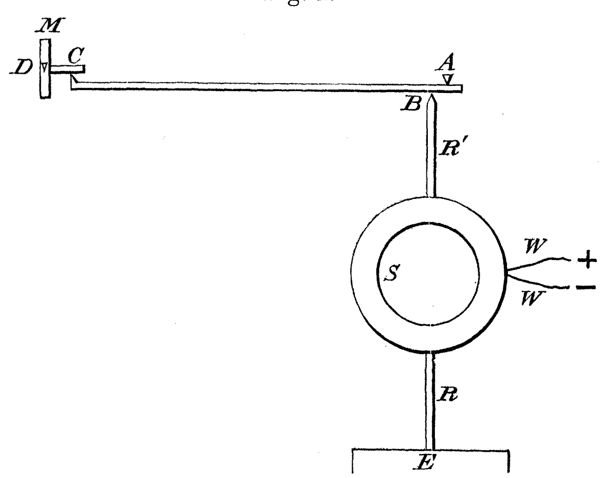
Each iron rod had rods of brass, 5·5 cm. in length soldered to the ends; the total length of the compound rod thus formed being 21 cm.

The magnetising solenoid used with the rods was as follows:—

Length	11·6 cm.
Diameter of wire	0·12 cm.
Number of turns	876
Field at centre	92 × C. nearly.

The rods were fixed axially in the solenoid by means of corks at the two ends.

Fig. 2.



The nature of the measuring instrument employed is indicated in the diagram, fig. 2. A detailed description of it, with a drawing, is given in the former paper. The ring S, round which is wound the wire, whose ends are shown at W, W, is placed in a vertical position, the lower end of one of its rods R resting in a conical recess in a brass base plate E. The upper end of the other rod R′, which is chisel-shaped, acts at B upon a brass lever, one end of which abuts upon a fixed knife edge A, and the other upon a short arm fixed perpendicularly upon the back of a small circular mirror M, which turns on knife edges D about its horizontal diameter. Shallow obtuse-angled notches are cut in the lever at A and B, and in the mirror arm at C. By means of a lantern, illuminated by a lime light, the image of a horizontal wire is, after reflection from the mirror, projected upon a distant vertical scale. A very slight deflection of the mirror causes a considerable movement of the image. The actual dimensions are as follows:—The distance AB = 10 mm., AC = 170 mm., MC = 7 mm.; the distance from the mirror to the scale was in all the experiments described in the present paper 7320 mm. (24 feet). The multiplying power therefore (remembering that the angular deflection of the beam of light is twice that of the mirror) was

$$\frac{7320 \times 170 \times 2}{7 \times 10} = 35{,}554 \text{ times.}$$

Each division of the scale = $\frac{1}{40}$ inch, = ·64 mm. Therefore a movement through one scale division indicated a difference in the diameter of the ring, or the length of rod, under examination of

$$1/35554 \text{ of } 0{\cdot}64 \text{ mm.} = 0{\cdot}000018 \text{ mm.*}$$

Since the mean diameter of the rings is 60 mm., one scale division corresponds to

$$0{\cdot}000018/60 = 0{\cdot}0000003 \text{ of diameter,}$$

or three ten-millionths.

The rods being 100 mm. long, one scale division indicates 0·00000018, or 1·8 ten-millionths of their length.

The optical arrangements were very perfect, and it was easy to read to half a scale division, or less, with accuracy.

The currents were measured by one of AYRTON and PERRY's ammeters, having a commutator by means of which the coils could be arranged either in series or in parallel, the deflections in the former case being ten times as great as in the latter. The instrument had been recently calibrated and was checked by reference to a tangent galvanometer. The ammeter being nearly dead-beat, the circuit needed to be closed only for a very short time in taking a reading. But it was found necessary in the experiments with the rings to switch the current through a coil of the same resistance before measuring it. The coils employed for this purpose were wound with the same kind of wire as that used for the rings. The ammeter was read to a quarter of a scale division.

The experiments were conducted as follows:—

(*a*) The ring or rod was demagnetised.

(*b*) A certain current was passed for a moment through the magnetising coil and the deflection indicating elongation or retraction was noted.

(*c*) The same current was passed a second time and the deflection noted. This was generally different from that given by (*b*).

(*d*) The iron was once more demagnetised.

* Seven ten-millionths of an inch.

(*e*) The same current was again sent through the coil, and the consequent deflection was the same (or nearly so) as in (*b*).

(*f*) The current was passed through the coil for the fourth time, and the resulting deflection was about the same as in (*c*).

The mean of the deflections found in (*b*) and (*e*) was taken as giving the true elongation or retraction produced in a previously *demagnetised* ring or rod by a given current. The mean of (*c*) and (*f*) gave the changes which occurred when the iron had been permanently magnetised by the same current. To these latter no great importance is attached.

The above series of operations was repeated with every different current that was passed through the magnetising coil.

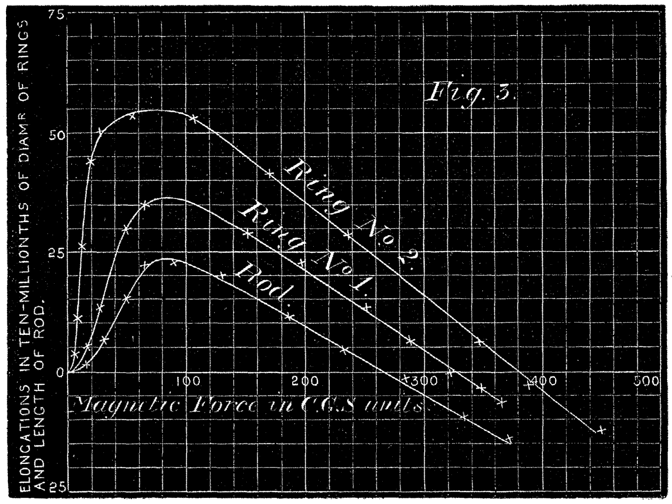
Table I. gives the results of experiments made with the three iron rings and with the rod No. 2. The magnetising forces are expressed in C.G.S. units and the elongations as ten-millionths of the diameter of the rings and the length of the rod. These results, except as regards ring No. 0 (which are omitted to avoid confusion), are plotted as curves in fig. 3, the abscissæ representing the magnetising forces and the ordinates the corresponding elongations. The curve of ring No. 0 would, if plotted, ascend very near to that of No. 2, and descend almost in a straight line with that of No. 1, its apex being about midway between the two.

TABLE I.—IRON.

Magnetising forces are expressed in C.G.S. units; elongations in ten-millionths of the diameter or length.

Ring No. 0.		Ring No. 1.		Ring No. 2.		Rod No. 2.	
Magnetising force.	Elongation.	Magnetising force.	Elongation.	Magnetising force.	Elongation.	Magnetising force.	Elongation.
1	3	19	5	6	4	16	1·8
9	24	26	13	8	11	22	5·4
13	30	49	30	12	26	29	6·3
23	42	66	35	20	44	47	15
39	45	152	29	31	50	65	23
68	42	198	23	56	53	90	23
97	36	248	14	107	53	128	20
123	33	292	6	172	41	187	12
		321	0	234	29	237	4·5
		350	− 3	351	5	287	− 1·8
		364	− 6	391	− 3	337	− 10
				449	− 12	374	− 14

Fig. 3



Upon examination of these curves it at once appears that the general character of the phenomenon under discussion is just the same in rings as it is in rods. In both cases a continually increasing magnetising force is accompanied by elongation, which reaches a maximum, then falls to zero, and ultimately becomes negative. And both sets of curves appear to follow a similar law, ascending in a form suggestive of a parabola, descending in a straight line. Greater differences might easily be found to occur in rings of different specimens of iron than those which exist between the rings and the rod in the present instance. The maximum elongation (23 ten-millionths) of the rod which happened to be chosen for these experiments is indeed less than that of any of the rings, and its retraction begins at an earlier stage. This, no doubt, is partly owing to the effect of the ends and to want of uniformity in the magnetisation, some portions of the rod having attained the state of maximum extension while others had either not yet reached it, or had passed it. But it may also be to a great extent due merely to the quality of the iron, for I have myself observed in an iron rod a maximum extension of as much as 45 ten-millionths* (equal to the maximum extension of ring No. 0 and greater than that of ring No. 1), while an elongation of 56 ten-millionths (greater than that of any of the rings) has been recorded by JOULE.† On the other hand, the maximum extensions of the rings would undoubtedly have been less if they had been made of harder iron, instead of the softest which was conveniently procurable.

* 'Roy. Soc. Proc.,' vol. 40, 1886, p. 117.

† See JOULE's paper, 'Phil. Mag.,' vol. 30, 1847, p. 76, or the Physical Society's 'Reprint,' p. 235. The greatest elongation recorded occurs in Exp. 2, p. 240. It amounted to 28 scale divisions, each of which corresponded to an extension of 1/138528 inch in a rod 36 inches long.

$$28/36 \times 138528 = 0\cdot0000056$$

or 56 ten-millionths of the length of the rod.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

It may, perhaps, be well to state briefly here, though more will be said on this point in an appendix to the paper, that each ring or rod has its own peculiar curve, which is perfectly definite and is at any time obtainable by the method above described without material variation.

Being thus satisfied that these curious effects of magnetism are, except as to mere details, independent of the form of the iron, and having regard to the fact that it is much easier to obtain intense fields with straight than with circular coils, I thought it worth while to continue the experiments upon rods only. The metals used, in addition to iron, were cobalt, nickel, manganese-steel, and bismuth.

The *iron* rod was that already described as No. 1.

The *cobalt* rod was obtained as a rough casting from Messrs. JOHNSON and MATTHEY. It was turned in the lathe to a cylindrical form, and, when finished, its diameter was 7·1 mm., and its length 67 mm. A single scale division, therefore, corresponds to 2·7 ten-millionths of its length.* Brass rods were soldered to its ends as usual.

The *nickel* used was in the form of a strip 100 mm. long, 9 mm. wide, and 0·75 mm. thick.

The *manganese-steel* rod was given to me by Dr. FLEMING, who obtained it from Messrs. HADFIELD. It was said to contain 12 per cent. of manganese. Its length was 100 mm., and diameter 4·5 mm. A scale division corresponds to 1·8 ten-millionths of both the nickel and the manganese-steel rods.

The *bismuth* was a cast rod procured from Messrs. JOHNSON and MATTHEY. Its length was 132 mm., and diameter 7 mm. One scale division represents 1·4 ten-millionths of its length.

The results of a series of experiments with the iron, nickel, and cobalt are given in Table II. and plotted in fig. 4. The mode of operating was exactly the same as that before described, each rod being demagnetised before every observation recorded in the Table.†

* For each scale division corresponds to 0·000018 mm., or, since the length of the cobalt is 67 mm., to 0·000018/67 = 2·7 ten-millionths of length.

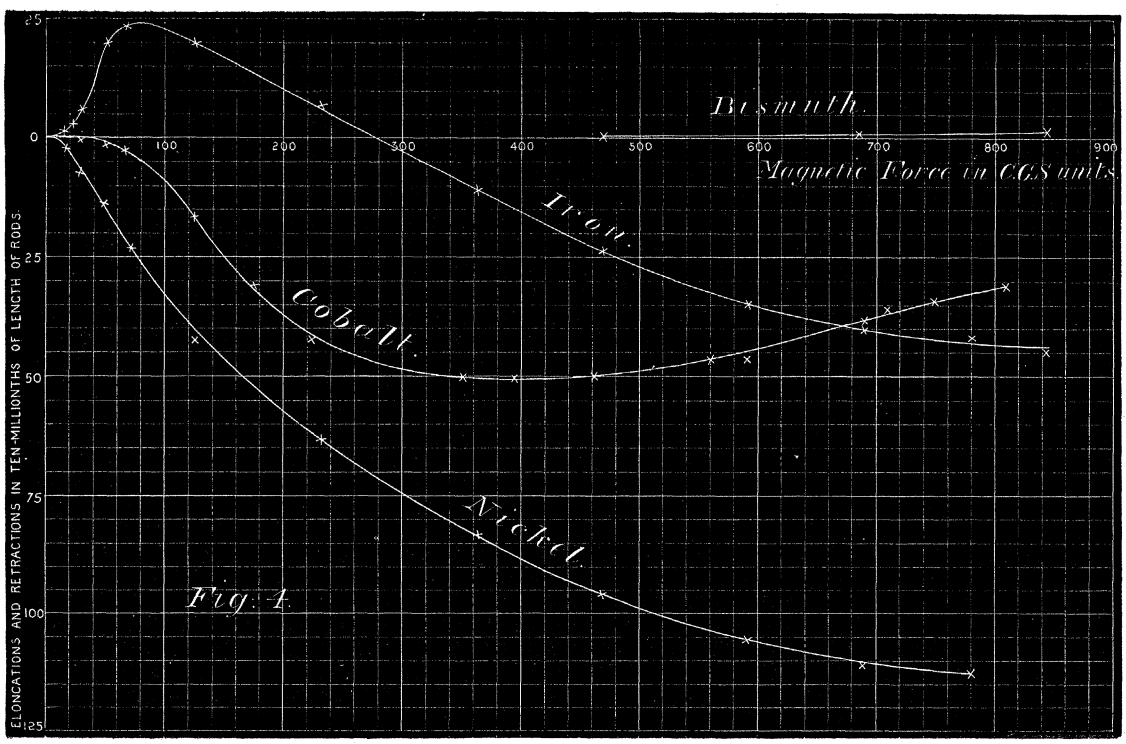
† The experiment with nickel was made immediately after that with iron, and the number of battery cells used was, after the first two currents, increased similarly in both cases. It was found that, owing to the constancy of the battery, the ammeter readings in the nickel experiment were, from the third to the ninth currents, practically identical with those obtained in the iron experiment. It was, therefore, assumed that they would be the same with the last three currents, and these were not actually read. Thus the metal was not unnecessarily heated by strong currents, which was a matter of great importance, the magnetic behaviour of nickel being far more sensitive to slight changes of temperature than that of iron or cobalt.

TABLE II.—Iron, Nickel, and Cobalt.

Iron.		Nickel.		Cobalt.	
Magnetising force.	Elongation.	Magnetising force.	Retraction.	Magnetising force.	Retraction.
16	1·8	13	0	31	0
22	2·7	18	1·8	47	1·4
31	6·3	29	7·2	65	2·7
49	20	50	14	125	16
69	23	69	23	175*	31
125	20	125	42	224	42
231	7·2	231	63	352	50
362	— 11	362	83	393*	50
468	— 24	468	96	462	50
592	— 35	592	105	561*	46
686	— 40	686	111	592	46
780	— 42	780	113	686	38
842	— 45			718*	36
				749	34
				811	31

Magnetising forces are expressed in C.G.S. units; elongations and retractions in ten-millionths of length.

Fig. 4.



* Observations made with descending currents.

It appears that the retraction undergone by the iron continues to increase with increasing magnetising forces until its amount is nearly twice that of the greatest elongation. But towards the end of the experiment there are indications that a limit is nearly reached.

The nickel curve is of the same character as that which I have already published, but it goes further, and the retraction is finally as much as 113 ten-millionths of the length. The beginning of the curve is slightly different from that given in my former paper. This difference was found to be accounted for by the fact that the nickel there referred to was permanently magnetised.

The curve showing the results of the cobalt experiment is of the most remarkable nature. No evidence of any change of length appears until the magnetising force exceeds 30 or 40 units. Then the length of the rod begins to diminish, and continues to diminish until the force reaches about 400. But beyond this point the rod gradually becomes longer, and the retraction with a force of 800 units is only three-fifths of its maximum amount.

[In showing some of these experiments at the conversazione of the Royal Society on May 9th, 1888, I had the privilege of taking my current from the large secondary battery used for lighting the building. By means of this it was found possible to carry the field up to about 1350 units, a far higher degree of intensity, I believe, than had ever been previously obtained for any experimental purpose without the use of electro-magnets. In this field the cobalt rod was *elongated*, the extent of its elongation being about half that of its greatest retraction in weaker fields. The cobalt curve in fig. 4 would therefore, if prolonged, cut the horizontal axis, probably at about 1100 (at which point there would be neither retraction nor elongation), and would continue on the upper side of the axis. Iron and cobalt, therefore, behave oppositely. With continually increasing magnetising force iron is at first extended and afterwards contracted, while cobalt is at first contracted and afterwards extended. —May 14th, 1888.]

It is difficult to imagine what can be the physical meaning of this effect. The possibility suggested itself that cobalt might acquire a maximum magnetisation with a magnetising force of about 400, further increase of the force resulting in a diminution of the magnetisation. The importance of establishing such a property in any substance* induced me to make some experiments upon the magnetisation of cobalt in strong fields,† but there was no indication of any such maximum as was looked for, the magnetisation being still on the increase when the experiment was stopped with a force exceeding 700.

It would be interesting to ascertain whether the retractions of iron and nickel

* See MAXWELL'S 'Electricity,' vol. 2, § 844.

† In ROWLAND'S experiments ('Phil. Mag.,' vol. 48, 1874) the magnetising force was not carried beyond 147 C.G.S. units.

would under higher forces exhibit the same peculiarity as that of cobalt. A comparison of the three curves seems to favour such a conjecture, but I cannot test it with the apparatus at present at my disposal.*

No result was anticipated from the experiment with the bismuth; but with high forces it was found to exhibit elongation. The effect, though small, was quite unmistakable, and even roughly measurable. It was certainly not due to heat, the elongation occurring instantly when the current was turned on, and disappearing as suddenly when the current was stopped. Nor do I think it could be accounted for by the presence of iron as an impurity. The results may be stated as follows:—

Magnetic force.	Elongation.
280	Suspected.
470	Quite perceptible.
680	0·25 scale div. = 0·3 ten-millionths.
842	1·25 scale div. = 1·5 ten-millionths.

Thus it appears that when the experiment was discontinued the elongation was increasing more rapidly than the field.

No alteration in the rod of *manganese steel* could be detected with forces up to 700 units. With 850 units there was a perceptible elongation, estimated at about one-tenth of a scale division, or one fifty-millionth part of the length of the rod.

Before the experiment there was no indication of any attraction between the steel and a delicately-pivoted compass needle, 22 mm. long, at a distance of two or three mm. After the magnetisation the steel had acquired sufficient polarity to draw the needle 20° from the magnetic meridian when held about 3 mm. from the opposite pole of the needle.

It must be admitted that it is not easy to form a plausible conjecture as to the physical causes of these magnetic extensions and retractions. It has been customary to explain the extension of soft iron by supposing its component molecules to be small magnets of elongated form, which, under the influence of a magnetising force, tend to set themselves in one direction; but to this view there are obvious objections. In any case, it seems probable that there are at least two influences, or sets of influences, at work, the one tending to cause extension, the other retraction. In the early stages of the magnetisation of iron the former predominates, but as the magnetisation advances it is overcome by the latter.

One of the influences tending to produce retraction must certainly be of a purely mechanical nature.

Suppose a uniformly magnetised rod to be transversely divided through the middle. The two halves, if placed end to end, will be held together by their mutual attraction,

* [I hope to have the opportunity of repeating all my experiments with more powerful currents than those hitherto used.—May 14th, 1888.]

pressing against each other with a certain force per unit of area, which can be measured by the weight necessary to tear one half from the other. The same pressure will exist between any two portions of the rod separated by any possible cross-section, and a certain longitudinal contraction of the rod will be the consequence. If now the rod, having been first demagnetised, be placed in a vertical position upon a fixed base, and loaded at the upper end with a weight equal to the greatest it could support when magnetised, it will undergo the same contraction as before, the compressional stresses being equal in the two cases. The amount of contraction occurring in this latter case is well known, and does not differ greatly in different kinds of iron. Does then this mechanical contraction completely account for the magnetic retraction which is observed in high fields ?

With the view of answering this question, I carried out a series of experiments upon the lifting powers of electromagnets in the form both of rods and of divided rings, the results of which have been communicated to the Royal Society.* It was found that the lifting power did not, as was generally believed, reach a practical limit with a comparatively small magnetising force, such as 135 or even 250 C.G.S. units.† It is true that after this latter point was passed the lifting power increased much more slowly than at first, but with a force of 600 units it was nevertheless upwards of 10 per cent. greater than with a force of 250, the weight supported being in the two cases 13,500 and 15,000 grammes per square centimetre, allowance having been made for the electromagnetic action between the iron and the coil.‡ Between these limits the increments of lifting power and magnetic force appear to be approximately proportional, the curve expressing their relation being a sensibly straight line.

Here, then, we have the means of comparing the mechanical with the magnetic effect. Taking 2040×10^6 as the value of YOUNG's modulus for wrought iron, in grammes weight per square centimetre, the contraction produced by loading the upper end with a weight of P grammes per centimetre is expressed as a fraction of the original length by $P/2040 \times 10^6$.

If $P = 13{,}500$ grms. (the weight per centimetre supported in a field of 250 units), the contraction will be

$$13500/2040 \times 10^6 = 0\cdot0000066,$$

or 66 ten-millionths of the length of the rod.

Again, if the rod be compressed by a load of 15,000 grms. (the weight supported in a field of 600 units), the contraction will be

$$15000/2040 \times 10^6 = 0\cdot0000074$$

* 'Roy. Soc. Proc.,' vol. 40, 1886, p. 486.

† See JENKIN's 'Electricity,' 7th edition, 1883, p. 124.

‡ It is, perhaps, questionable whether any deduction should be made on this account. The figures without such deduction would be respectively about 14,000 and 15,000 grms. But the difference is not sufficiently great to affect the argument.

or 74 ten-millionths of the length; *i.e.*, the contraction of the rod when longitudinally compressed by the weight which it could support in a field of 600 is only 8 ten-millionths greater than when it is compressed by the weight which it carried in a field of 250.

Now it appears from the tables and curves contained in the present paper that the *magnetic* contraction of an iron rod (or ring) is greater in a field of 600 than in one of 250 by as much as 40 ten-millionths. It follows, therefore, that what I have called the mechanical contraction only accounts for a fifth part of the total observed effect, or even less if it should be the fact, as is not unlikely, that the elongating influence upon which the contracting influence is superposed, does not altogether cease to increase after the *net* elongation has reached its maximum.

The main cause of the retraction, therefore, still remains a mystery.

It is proposed to continue these experiments, which must certainly tend to throw some light upon the molecular effects of magnetism.

APPENDIX.

The value to be attached to the results given in this paper depends greatly upon evidence of the precision with which measurements can be made of lengths commonly regarded as infinitesimal. In order that an estimate may be formed of the degree of accuracy arrived at, I have thought it desirable to give in the form of an appendix certain details of the experiments, which if contained in the paper itself would have been tedious and cumbersome.

As elsewhere stated, the optical arrangements are so perfect, and the edge of the focussed image of the wire is so sharp that, under favourable conditions, it is possible to read to a quarter of a scale division (1 scale division = 0·64 mm. = $\frac{1}{40}$ inch) even when the reflected beam of light is 732 cm. (24 feet) long. But during an experiment it unfortunately happens that, in consequence of the heating effect of the currents, which no amount of care can completely obviate, the image is in constant movement up or down the scale, a change of one degree in the temperature of the magnetised ring or rod, together with its brass connections, causing a rise or fall of more than 150 scale divisions. This not only renders it difficult to make an accurate reading, but it is the source of another and more serious inconvenience, namely, that there can be no fixed zero. Every observation of a deflection, therefore, involves two scale readings, in each of which there is a chance of error. The following was the method adopted. At the moment when the upper edge of the wire appeared in the course of its wanderings to coincide exactly with a certain previously determined division which it had been seen to be approaching, and the number of which was recorded as the temporary zero, the contact key was depressed, and the division nearest to which the image was deflected was quickly noted.* The difference between the two readings gave the deflection in scale divisions. The first of these readings was believed to be correct within less than a quarter of a scale division; the second within half a scale division. It is clear that the results of two such observations made under similar conditions and not unequally affected by any source of disturbance, such as temperature changes, ought not to differ by more than one scale division, and their mean should be correct to half a scale division. Now half a scale division corresponds to 0·000009 mm., or about 1 three-millionth of an inch, which is equivalent to $1\frac{1}{2}$ ten-millionths of the diameter of the iron rings and (approximately) of the length of the cobalt rod, and to a little less than 1 ten-millionth of the length of the rods of iron and nickel. This was the degree of precision aimed at. How nearly it was actually attained may be gathered from the detailed notes of some of the experiments contained in Tables III., IV., and V., which are given as specimens, and from the diagram fig. 5.

The tables consist of a transcript from the note-book of the actual figures recorded in the experiments to which they relate. Nothing has been altered or omitted, and nothing added, except the two final columns showing the results when reduced to magnetising forces and ten-millionths of length. The figures printed in heavy type are those which appear in Table II. Such of the figures as have been rejected (or, rather, amended) owing to evident mistakes are printed in italics.† This occurs in only two instances.

The experiments selected are those which relate to the "Iron rod No. 1" and the cobalt rod. The first is chosen both because it goes further than any experiment with the rings, and also because it affords an opportunity of comparing measurements taken on two different occasions. The figures relating to the cobalt are given in full, on account of the novelty and probable importance of the results obtained with that metal.

* This could only be done by a momentary glance, the circuit being necessarily closed for no more than about half a second to avoid heating: it was, therefore, not attempted to read to a fraction of a division.

† The error which most frequently occurred in making a rapid reading was to mistake a long "5-line" for the long "10-line" which came next above it on the scale. This mistake was generally detected and rectified the moment it was made, but in three or four cases, all of which are specified in the text, the wrong number was recorded. In these cases the observation was not actually rejected, but was corrected by subtracting five.

TABLE III.—Iron Rod, No. 1. December 19, 1887.

No. of cells.	Added resistance. Ohms.	Scale readings. First current after demagnetising. Off.	On.	Diff.	Second current. Off.	On.	Diff.	First current after demagnetising. Off.	On.	Diff.	Second current. Off.	On.	Diff.	Mean differences. For 1st current.	For 2nd current.	Am-meter.	Current. Ampères.	Mag. force = Current × 92.	Elongation = 1st mean diff. × 1·8.
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	7	60	61	1	50	51·5	1·5	9	10	1	7	8	1	1	1·25	1·25	0·17	16	1·8
1	5	184	186	2	183	185	2	180	182	2	180	182	2	2	2	1·75	0·24	22	3·6
1	3	178	182	4	180	184	4	179	184	5	180	184	4	4·5	4	2·25	0·31	29	8
1	1	185	196	11	188	198	10	187	198	11	189	198	9	11	9·5	3·75	0·51	47	20
1	0	188	201	13	190	201	11	192	205	13	197	209	12	13	11·5	5·50	0·75	69	23
2	..	200	211	11	202	211	9	205	216	11	210	219	9	11	9	10·50	1·42	131	20
4	..	215	217	2	217	218	1	220	223	3	222	223	1	2·5	1	19·50	2·64	243	5
7	..	235	226	− 9	239	228	−11	247	238	− 9	255	244	−11	− 9	−11	34·25	4·64	427	−16
10	..	310	295	−15	315	298	−17	150	135	−15	160	143	−17	−15	−17	41·75	5·66	521	−27
15	..	163	143	−20	168	145	−23	200	180	−20	205	182	−23	−20	−23	5·25	7·12	655	−36
20	..	255	233	−22	270	245	−25	295	273	−22	310	286	−24	−22	−24·5	5·75	7·80	718	−40
25	..	215	190·5	−24·5	230	203	−27	250	226	−24	280	254	−26	−24	−26·5	6·25	8·48	780	−43
30	..	113	89	−24	120	94	−26	155	130	−25	165	137	−28	−24·5	−27	6·50	8·81	810	−44
23	..	*240*	*212*	*−28*	250	225	−25	280	256	−24	290	265	−25	−23·5	−25	6·00	8·12	749	−42
14	..	220	201	−19	245	224	−21	270	251	−19	276	255	−21	−19	−21	4·75	6·44	592	−34
8	..	255	245	−10	275	263	−12	291	280	−11	293	281	−12	−10·5	−12	34·00	4·61	424	−19
3	..	177	185	8	181	186	5	173	180	7	175	180	5	7·5	5	15·00	2·03	187	14
1	..	138	152	14	140	152	12	133	146	13	133	144	11	13·5	11·5	5·50	0·75	69	24
1	2	105	112	7	101	106	5	84	91	7	80	86	6	7	5·5	3·00	0·41	38	13
1	4	60	63	3	59	61	2	46	48	2	45	47	2	2·5	2	2·00	0·27	25	4·5
1	6	20	20	1	19	20	1	5	6	1	4	5	1	1	1	1·50	0·20	18	1·8

TABLE IV.—Same Iron Rod. January 4, 1888.

No. of cells.	Added resistance. Ohms.	Scale readings.														Am-meter.	Current. Ampères.	Mag. force = Current × 92.	Elongation = 1st mean diff. × 1·8.
		First current after demagnetising.			Second current.			First current after demagnetising.			Second current.			Mean differences.					
		Off.	On.	Diff.	Off.	On.	Diff.	Off.	On.	Diff.	Off.	On.	Diff.	For 1st current.	For 2nd current.				
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	7	124	125	1	124	125	1	..	..	..	..	..	..	1	1	1·25	0·17	16	1·8
1	5	126	127·5	1·5	127	128	1	..	..	..	..	..	..	1·5	1	1·75	0·24	22	2·7
1	3	131	134	3	132	135	3	133	137	4	134	137	3	3·5	3	2·50	0·34	31	6·3
1	1	135	146	11	137	146	9	140	151	11	142	151	9	11	9	4·00	0·54	49	20
1	0	140	153	13	142	153	11	143	156	13	144	156	12	13	11·5	5·50	0·75	69	23
2	..	130	141	11	133	142	9	135	146	11	137	146	9	11	9	10·00	1·36	125	20
4	..	116	120	4	120	122	2	122	126	4	125	127	2	4	2	18·50	2·51	231	7·2
7	..	113	107	− 6	122	115	− 7	124	118	− 6	127	119	− 8	− 6	− 7·5	29·00	3·93	362	−11
10	..	127	114	−13	132	117	−15	141	127	−14	145	130	−15	−13·5	−15	3·75	5·09	468	−24
15	..	153	133	−20	160	138	−22	130	111	−19	140	119	−21	−19·5	−21·5	4·75	6·44	592	−35
20	..	165	144	−21	175	150	−25	187	165	−22	194	171	−23	−22·5	−24	5·50	7·46	686	−40
25	..	221	197	−24	235	210	−25	255	232	−23	265	239	−26	−23·5	−25·5	6·25	8·48	780	−42
30	..	300	274	−26	320	293	−27	355	331	−24	210	182	−28	−25	−27·5	6·75	9·15	842	−45
23	..	270	246	−24	294	268	−26	330	306	−24	341	311	−30	−24	−28	5·75	7·80	718	−43

TABLE V.—Cobalt Rod.

No. of cells.	Added resistance. Ohms.	Scale readings.														Am-meter.	Current. Ampères.	Mag. force = Current × 92.	Retraction = 1st mean diff. × 2·7.
		First current after demagnetising.			Second current.			First current after demagnetising.			Second current.			Mean differences.					
		Off.	On.	Diff.	Off.	On.	Diff.	Off.	On.	Diff.	Off.	On.	Diff.	For 1st current.	For 2nd current.				
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	8	120	120	0	..	..	..	..	..	..	..	..	..	..	..	1·25	0·17	..	..
1	5	121	121	0	..	..	..	..	..	..	..	..	..	..	..	1·75	0·24	..	..
1	3	127	127	0	..	..	..	..	..	..	..	..	..	..	..	2·50	0·34	**31**	**0**
1	1	159	158·5	0·5	167	166·5	0·5	..	..	..	..	..	..	0·5	0·5	3·75	0·51	**47**	**1·4**
1	0	186	185	1	187	186	1	190	189	1	192	191	1	1	1	5·25	0·71	**65**	**2·7**
2	..	239	233	6	241	235	6	262	256	6	267	261	6	6	6	10·00	1·36	**125**	**16**
4	..	281	266	15	282	266	16	283	267	16	284	268	16	15·5	16	18·00	2·44	**224**	**42**
7	..	293	275	18	295	276	19	299	280	19	300	281	19	18·5	19	28·25	3·83	**352**	**50**
10	..	314	296	18	318	299	19	327	308	19	330	311	19	18·5	19	37·00	5·02	**462**	**50**
15	..	280	263	17	285	268	17	301	284	17	305	288	17	17	17	4·75	6·44	**592**	**46**
20	..	155	141	14	160	145	15	180	166	14	185	170	15	14	15	5·50	7·46	**686**	**38**
25	..	242	230	12	255	242	13	290	277	13	300	287	13	12·5	13	6·00	8·14	**749**	**34**
30	..	100	89	11	110	98	12	140	128	12	150	139	11	11·5	11·5	6·50	8·81	**811**	**31**
23	..	260	246	14	270	257	13	305	292	13	315	303	12	13·5	12·5	5·75	7·80	**718**	**36**
14	..	145	128	17	150	133	17	175	158	17	182	166	16	17	16·5	4·50	6·10	**561**	**46**
8	..	226	207	19	*235*	*212*	*23*	260	242	18	265	246	19	18·5	18·5	31·50	4·27	**393**	**50**
3	..	290	279	11	295	284	11	316	304	12	320	309	11	11·5	11	14·00	1·90	**175**	**31**
1	..	322	321	1	324	323	1	..	..	..	..	..	..	1	1	5·25	0·71	65	2·7
30	..	167	155	12	168	157	11	171	159	12	172	160	12	12	11·5	6·50	8·81	811	32

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The tables contain twenty columns, which, for convenience of reference, are lettered from A to T.

A gives the number of GROVE'S cells used.

B the resistance in ohms inserted to vary the current when only one cell was in use.

C shows the scale divisions indicated immediately before the circuit was closed (*i.e.*, the temporary zero), the metal having been recently demagnetised.

D gives the readings obtained on closing the circuit for the *first* time after demagnetisation.

E contains the differences of C and D, giving the elongations or retractions in scale divisions.

F gives the scale readings immediately before the circuit was closed the second time (another temporary zero). Owing to small changes of temperature, the position of the wire was nearly always different by several divisions from that denoted in column C.

G gives the deflections when the circuit was closed for the *second* time after demagnetisation.

H contains the differences of F and G.

I, J, K are repetitions of C, D, E, the rod having been again demagnetised.

L, M, N are repetitions of F, G, H.

O gives the means of E and K.

P the means of H and M.

Q contains the ammeter readings of the currents.

R the currents in ampères obtained by multiplying the ammeter readings by the factor 0·1356 or 1·356, according as the coils of the instrument were arranged (by the commutator) in series or in parallel.

S gives the field at the middle of the coil, obtained by multiplying the ampères by 92.

T shows the elongations and retractions in ten-millionths of length obtained by multiplying the figures in column O by 1·8 for the iron and by 2·7 for the cobalt.

The first of the experiments with the iron rod was made on Dec. 19, 1887, the second on Jan. 4, 1888, the whole apparatus having been in the meantime dismantled and the rod removed from the coil, which had been used for another purpose.

In the first experiment currents of descending as well as of ascending strength were used. In the second only one smaller current was applied after the strongest, the experiment being then stopped.

The following points should be noticed :—

(1.) The very close agreement between the results obtained on different days, particularly with the smaller currents. Such variations as exceed the specified limits of observational errors may be fully accounted for by small differences of temperature affecting the susceptibility of the iron.

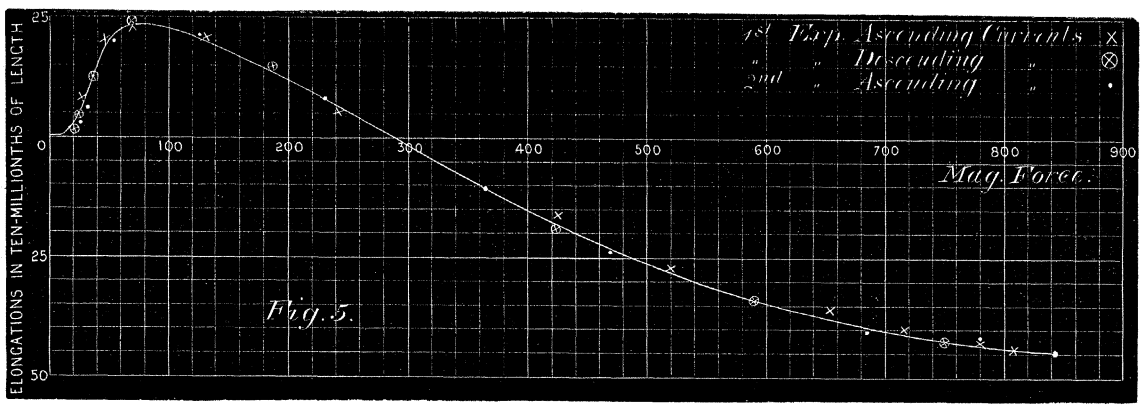
(2.) The close agreement between the deflections obtained with ascending and with descending currents. As before, changes of temperature would account for the greater part of such differences as exist.

(3.) In the thirty-three pairs of observations recorded in columns F and K, there is only one instance in which the discrepancy exceeds a single scale division, and in that case the full battery of 30 cells was in use.

This shows that the degree of precision aimed at was practically attained, at least in the final results, which are the means of two observations.

The greatest reasonably possible combination of errors in the measurements of the parts of the apparatus and of the distance of the mirror from the scale would not, even assuming that they all conspired together in one direction, affect the results to a greater extent than about 1 per cent. It may therefore be taken as exceedingly probable that the figures recorded in the table correctly represent to one ten-millionth part of the length of the rod the elongations and retractions which actually occurred. The slight variations in the results obtained upon different days or when the order of the currents was reversed are mainly due to differences in the physical condition of the iron (thermal or magnetic), and not to instrumental or observational errors.

Fig. 5.



In order that an idea may be formed of the extent of such variations, the diagram fig. 5 has been constructed, in which the three series of observations have been plotted together, the points belonging to each different series being distinguished by a different kind of mark. Those of the first experiment with *ascending* currents are marked with crosses; those of the same experiment with *descending* currents are marked with crosses surrounded by circles; and those of the second experiment with ascending currents are distinguished by dots. A smooth curve is drawn through all the marks.

There is only one instance in which a point appears to deviate from the curve by a distance equal to as much as half the height of one of the small square spaces, namely, when the magnetic force is about 425 units. Now the height of one of these spaces corresponds to five ten-millionths of the length of the rod; or, since the rod is four inches (10 cm.) in length, to an absolute length of two-millionths of an inch. Half the height of a space, therefore, represents a length of one-millionth of an inch,* and this is the widest deviation which occurs in the whole of the three series of observations. It is clear that in the great majority of cases the deviation from the mean curve is very much less, not often being so great as one-fifth of a space height, or one two-and-half-millionth part of an inch.

The close agreement of columns E and K also shows how perfectly the demagnetising apparatus fulfilled its object. It appears from columns H and M that the elongating effect of the second current after a demagnetisation was generally different from that of the first, the difference being of course accounted for by permanent magnetism.†

The figures giving the remarkable cobalt curve are just as regular as those which relate to the iron. In the results of the 14 pairs of observations in columns E and K there is not a single discrepancy of more than 1 scale division. Observations were made both with ascending and with descending currents, all of which are plotted in fig. 4. It was not until after the experiment was nearly completed that my attention was called to the fact of the retraction reaching a maximum with currents of medium strength, and falling off when stronger currents were applied. Thinking that this might possibly be an effect of heat upon susceptibility, I put on all the 30 cells at once, the metal having been first allowed to become quite cool. The deflection was, however, just the same as that which the 30 cells had produced before.

There can be no doubt that the curve in fig. 4 correctly represents the effect of magnetisation upon the length of my rod of cobalt. Whether all specimens of the metal would behave in exactly the same manner is not so certain. Professor BARRETT found‡ that cobalt was elongated when magnetised. From the analogy of iron it seems not unlikely that a *softer* rod of cobalt than mine would in the earlier stages of magnetisation undergo some elongation; but it is more than probable that with sufficiently high magnetic forces such elongation would be ultimately converted into retraction of the kind indicated by the curve in fig. 4.

In the experiments with ring No. 0 the observations were only made once, so that their individual accuracy cannot be tested by comparison.

* About one-twentieth part of the wave-length of green light.

† [It appears from a comparison of the figures in columns O and P of Tables III. and IV. that the permanent elongation which remains when the magnetising force has been withdrawn increases until the magnetising force which produced it reaches about 130 units, after which it is nearly constant. It has been pointed out that this fact tallies well with the known constancy of residual magnetism when the fields are strong.—May 14th, 1888.]

‡ 'Nature,' vol. 26, 1882, p. 585.

In the case of ring No. 1 (the experiment upon which, as upon all others except ring No. 0, was conducted exactly in the manner described for the iron rod No. 1 and the cobalt rod) there was no discrepancy greater than 1 scale division in the two series of 13 observations (columns E and K), except in one instance when there was evidently a mistake.

The number of pairs of observations with ring No. 2 was 19, in 14 of which the discrepancy did not exceed 1 division. Of the five greater discrepancies all but one occurred with descending currents, when the ring was suffering from the heating effect of the full battery. There is some reason to believe that the demagnetisation was not so perfect in this experiment as in the others.

Eleven pairs of observations were made with the iron rod No. 2. In two cases there were discrepancies of 2 divisions; no other discrepancy exceeded 1.

In consequence of the very great effect produced by small changes of temperature upon the susceptibility of nickel, the pairs of observations with this metal were not nearly so concordant as those with iron and cobalt. The number of double observations made was 11. With 5 of these (including a case in which there was an evident misreading of 5 divisions) the discrepancy did not exceed 1; twice it was 2, three times it was 3. One observation of a pair was rejected on account of the evident fact that the demagnetisation had been accidentally omitted.*

But, though the discrepancies are great in comparison with those which occurred with the other metals, their absolute magnitude is very small, and it is not probable that any point in the nickel curve, fig. 4, is in error by so much as a millionth of an inch,† or two ten-millionths of the length of the strip.

ADDENDUM.

Received June 5, 1888.

THROUGH the great kindness of Mr. W. H. PREECE, F.R.S., who allowed me the unrestricted use of the large battery of secondary cells employed in lighting his residence at Wimbledon, I have been able to repeat some of my experiments with much stronger magnetising currents.

The instrument and the magnetising coil used and the mode of working were exactly the same as before, but it was thought desirable to vary the samples of the metals, in order that it might appear how far the peculiarities already noticed were independent of the particular specimens which had been examined.

* The demagnetising process involved eight separate operations, including the closing and opening of switches. The omission of any one of these might render the process of no effect.

† When the discrepancy was 3 scale divisions the probable error of the mean = 0·67 × 1·5 = 1 scale division = 0·000018 mm. = 0·00000072 inch (or less than a millionth) = 0·00000016 of the length (or less than two ten-millionths).

The *iron* was a piece of soft charcoal wire, 7·5 cm. in length, and 0·32 cm. in diameter. The *nickel* was also a drawn wire, its length being 7·5 cm., and diameter 0·3 cm. The *cobalt* was a short rod turned from a cylindrical casting. When finished its length was 4·1 cm., and diameter 0·5 cm.

The nickel and cobalt were supplied by Messrs. JOHNSON and MATTHEY, who prepared them expressly for these experiments. Both were probably purer than the specimens previously used. The new cobalt rod in particular was much softer than the old one, and no great difficulty was experienced in turning it in the lathe—an operation which I performed myself.

The results of a series of experiments with these rods are given in Table VI., and plotted as curves in fig. 6, the points at which observations were made being distinguished by crosses.

It was not attempted, and, indeed, under the circumstances, it would not have been possible, to make the observations with the same degree of precision as in the first described experiments. The values of the elongations and retractions are therefore given in two-millionths of the lengths (expressed for convenience as multiples of five ten-millionths) instead of in ten-millionths. To this degree of approximation identical values of the elongations could be obtained for the same magnetising forces with tolerable certainty, and the accuracy of the tabulated results may be accepted as amply sufficient for the purpose in view.

TABLE VI.

Magnetic field in C.G.S. units.	Elongations in ten-millionths of length.		
	Iron.	Cobalt.	Nickel.
35	..	..	−85
100	15	−10	−135
220	..	−25	..
310	0	−45	−210
500	−35	−30	−225
625	..	−20	−235
745	−50	0	−245
875	..	15	..
960	−60	30	−245
1120	−65	45	−240
1215	..	55	−250
1305	−65	65	−245
1400	−66	75	−245
1500	−65	..	..

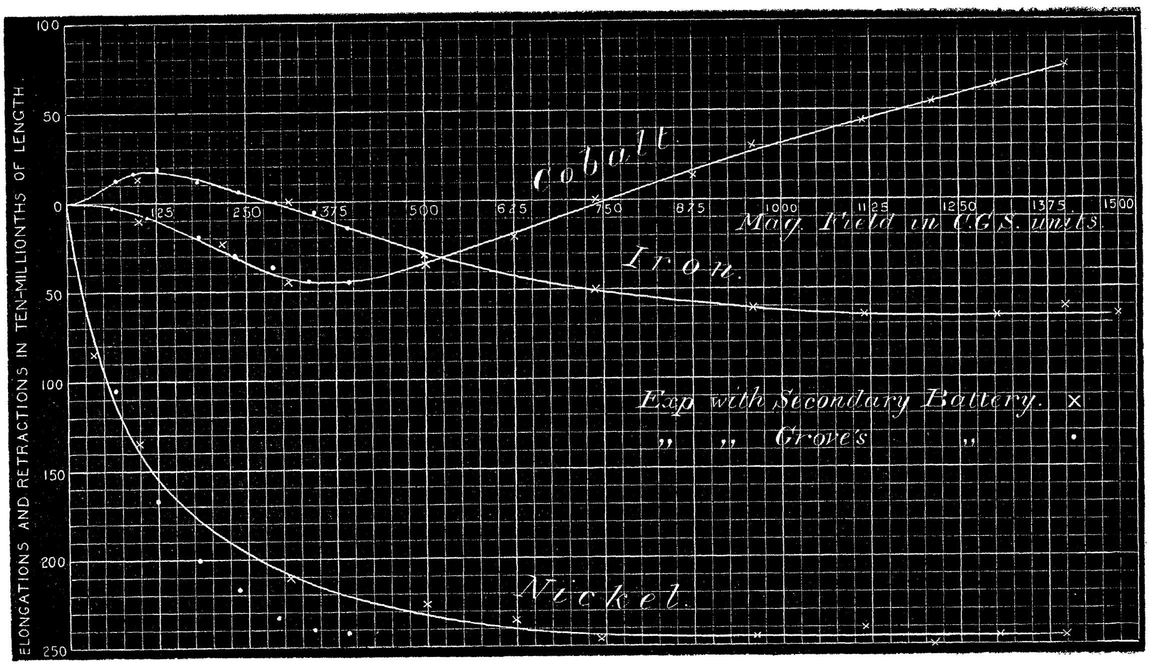
NOTE.—Where no observations are recorded none were made.

A second series of observations with magnetising forces up to about 400 units was subsequently made in my own laboratory (a battery of seven GROVE'S cells being employed) in order to arrive at a more definite determination of those portions of the curves where greater detail seemed to be required. The corresponding values of magnetising force and change of length thus obtained are given in Table VII., and indicated by dots in the diagram fig. 6.

TABLE VII.

Magnetic field in C.G.S. units.	Elongations in ten-millionths of length.		
	Iron.	Cobalt.	Nickel.
65	13	0	−104
90	17	..	..
112	..	− 8	..
125	19	..	−167
181	13	−19	−199
237	7	−31	−218
293	0	−37	−233
343	− 6	−44	−240
393	−13	−43	−242

Fig. 6.



Referring to this diagram, it will be seen that in the cases of iron and cobalt the coincidence of the two sets of observations is as close as could be expected. The earlier portions of these curves have, in fact, been drawn through the dots without any regard to the position of the crosses. But for nickel the two series of results diverge very considerably. The curve is here drawn as smoothly as possible through the crosses, and the dots are seen to lie evenly and regularly a little below it. A discrepancy of this kind might, under the circumstances, have been foreseen. It is beyond doubt due to the fact which I have frequently noticed and already remarked upon in this paper, that the degree of retraction which nickel undergoes when magnetised is materially affected by differences of temperature,* a fact which may be explained by the well-known influence of heat in diminishing the magnetic susceptibility of that metal. Now the temperature of Mr. PREECE's engine-room on the afternoon of May 25, when the secondary battery experiments were carried out, was most uncomfortably high, whereas the air of my laboratory when the other experiments were made, three days later, was bitterly cold. Unfortunately no thermometer readings were taken, but the difference of the temperatures on the two occasions could not have been less than 10° C. Such a difference is, I think, sufficient to account for the discrepancy of the two series of results.

The results of the experiments referred to in this *addendum* may be stated as follows.

Save as to mere details, which may be expected to vary more or less with different specimens of the metals used, according to their purity and physical condition, the results lastly obtained are in agreement with the former ones, so far as these go.

With regard to details, the new specimen of cobalt reaches its maximum retraction at an earlier stage than the old one, namely, at about 300 units instead of 400. Both, however, agree in not yielding the smallest indication of either retraction or elongation in weak fields.

The retraction exhibited by the new nickel rod is enormous, being for equal magnetising forces more than twice as great as that of the old one, and ultimately amounting to nearly 1/40000th part of its length. I believe this to be accounted for by its superior purity.

The new iron curve differs from that in fig. 4 in showing a somewhat smaller maximum elongation and a greater amount of retraction, but the two are of just the same general character.

The latest results are so far merely confirmatory of the earlier ones. But they go further, and afford information concerning the behaviour of the metals in far stronger fields than were before obtained.

They show clearly that the retractions of iron and of nickel reach a limit in fields of a certain intensity, about 1000 for iron and 800 for nickel in the specimens examined, the retraction in stronger fields being neither greater nor less. My conjecture that a minimum length might possibly be passed is therefore not supported.

On the other hand, it appears that the length of the cobalt rod, after passing through a minimum, regains its original value in a field the strength of which is for this particular rod about 750 units, and then rapidly increases, the increments of length

* I find that Professor BARRETT had observed this effect of heat. 'Nature,' vol. 26, 1882, p. 586. —June 13, 1888.

and of magnetising current being nearly proportional when the experiment was stopped with a field of 1400 units. The actual elongation was then about four times as much as the maximum elongation of the iron rod.

It is clear that so far as cobalt is concerned the subject is not yet exhausted, though the further experimental investigation of it would not be easy. A limit to the intensity of the magnetic field, which can be produced by a coil of given dimensions, is imposed by the heating effect of the current,* and this limit was practically reached in my experiments. With a larger coil, and a suitably adapted instrument, stronger fields could undoubtedly be obtained without either serious heating or sacrifice of uniformity; but the battery power necessary for such a coil would be disproportionately great, so great, indeed, that for any considerable increase of the field it would not be easily obtainable.

It is unlikely that a field suitable for these experiments could be produced by means of an electro-magnet. For the present, therefore, our knowledge as to the behaviour of cobalt under magnetisation must remain incomplete.

In conclusion I have to express my hearty thanks to Mr. PREECE for having so freely placed at my disposal the resources of his valuable electrical installation.

* The quantity of heat generated in the coil per unit of time varies as the square of the magnetic field.