XVI. *On Electrotorsion.* *By* George Gore, *F.R.S.*

Received November 26, 1873,—Read January 8, 1874*.

Wiedemann has experimentally examined† the influence of magnetism upon the mechanical torsion of iron wire, and has shown that an iron wire hung in the centre of a helix and twisted is more or less untwisted when a current traverses the helix. But as the torsion in his experiments was produced by the combined influence of a voltaic current and previous mechanical twist, and is quite a distinct phenomenon from that produced by the combined influence of electric currents only, which forms the subject of this communication, and as no one appears to have discovered the particular class of phenomena which are treated of in this investigation, I take an opportunity of making known my experiments and the new facts I have found.

[Since the publication of the abstract of this paper in the 'Proceedings of the Royal Society,' vol. xxii. p. 57, January 8, 1874, Professor Wiedemann (to whom I had sent a copy of that abstract) has kindly written to me as follows:—"You have found independently some results which I had already published in the year 1862 in Poggendorff's 'Annalen,' vol. cxvii. p. 208. A short abstract of these experiments is also given in my 'Treatise on Galvanism, &c.' (1st edition, vol. ii. p. 445; 2nd edition, vol. ii. p. 565), where you will find my complete theory of the relations between magnetism and torsion."]

1. *Apparatus employed.*

I took a voltaic helix, 2·45 metres long and 1·5 centimetre internal diameter, of insulated copper wire 1·8 mm. thick, coiled as a double conductor and in two layers. To form a tube upon which to coil the wire, two half-round strips of wood, with a semicircular groove in each, were glued together, and the superfluous glue removed from the interior whilst still warm by means of a rope soaked in hot water. A brass tube may be used instead of the wooden one, as it does not prevent the torsions. The helix was fixed in an upright pillar of wood (Plate XLII. fig. 1), and a string $2\frac{1}{2}$ metres long, supporting a leaden bullet, was attached to a pin near the top of the coil to enable the apparatus to be placed vertical.

A straight rod of soft iron, 2·6 metres long and 11 mm. diameter, was entirely enclosed, except its ends, within the helix, and securely suspended by a brass clamp.

* The passages enclosed in square brackets were added in July 1874.

† Wiedemann's 'Die Lehre von Galvanismus und Elektromagnetismus,' vol. ii. p. 559; Pogg. Ann. vol. ciii. p. 571, May 1856, and vol. cvi. p. 161, 1859; Annales de Chimie, vol. liii. 1858, p. 379, and vol. lvi. p. 373, 1859.

screw attached to its upper end and fixed to the top of the wooden support. To the lower and free end of the bar was fixed by a screw a movable and rigid horizontal pointer of brass, 47 centims. long, weighing about 300 grammes ($=10\frac{1}{2}$ ounces), and balanced by an adjustable counterpoise. In a few experiments, where rapid and continuous *vibration* was required, the free end of the pointer was tipped with a thick piece of platinum wire.

With this apparatus the torsional movements were sufficiently large not to require the employment of the method of detecting and measuring them by means of a mirror and telescope, or luminous image reflected to a distant graduated scale. The lower end of the iron rod had fixed to it a vertical piece of thick platinum wire about 3 centims. long, which dipped into mercury contained in a little platinum cup separately supported by a horizontal rod of copper to act as a conductor; or it had sometimes attached to it by means of a screw, B (fig. 2), a strong loop of copper, A, for the purpose of supporting a weight, and provided with a stout platinum wire (C) to dip into the mercury. Instead of the axial bar, a wire of iron, about 2 mm. thick, was generally employed, and the torsions obtained with it were much greater. The helix was excited by means of 6 or 12 GROVE's elements, each of about half a litre (or one pint) capacity, and having platinum plates 10 centims. long and 8 centims. wide.

The current from 4 or 6 of those cells, in double series, being now passed in an uninterrupted state through the coil, and simultaneously with it, or during its passage, the one from the remaining 6 or 8 cells, in double row, being passed through the bar or wire, the index moved either to the right hand or the left, according to the directions of the currents.

By fixing a platinum-tipped horizontal brass screw upon a separate support, so that the screw just touched the side of the platinum end of the pointer, and completing the axial circuit through it, continued vibration of the pointer was obtained, provided the screw was placed on the proper side and the index was sufficiently rigid.

The more conspicuous effects may be successfully obtained with a much smaller apparatus.

In all cases the torsion was accompanied by elongation, and the resulting motion was in a diagonal direction, and the maximum of vibration was therefore obtained by placing the contact-screw so as to touch the index between its side and upper surface. By placing the screw in such a position that the vertical movement alone did not break the contact, rapid vibration, due to torsion only, could be maintained during any length of time; and by placing it in contact with the upper surface of the pointer and passing the current through the coil and index only, continued vibration, due entirely to elongation, could also be readily obtained.

2. *Does an axial electric current lengthen an iron bar?*

To ascertain this I passed the current through the bar only; but not even a tendency to vertical vibration could be perceived. I also tried a thinner rod, and a wire strained by a weight, and applied the contact-screw to the *under* side of the index (as well as to the upper), in order to detect any shortening, but obtained no positive results; probably an extremely minute degree of shortening occurred, and was counterbalanced by expansion produced by heat of conduction-resistance.

3. *Methods and conditions of obtaining the torsions.*

The torsions may be produced:—(1st) by the passage of axial currents alternately in opposite directions, (2nd) by the alternate passage of coil-currents and axial ones, (3rd) by the simultaneous passage of both, and (4th) by the temporary passage of an axial current during the continuance of a coil one, or *vice versâ*. The 1st and 2nd methods yield only very small torsions, and the 3rd and 4th produce exceedingly large ones.

The best conditions are:—a slender wire of the softest iron, with but little weight attached to it, and free from mechanical twist, enclosed nearly its entire length in a powerful voltaic coil; a downward current in the iron wire simultaneous with a coil-current producing a north * pole below; and repeatedly applying the pair of currents synchronously with the movements of the index (the two currents may be made simultaneous in their action by causing them either to leave the two batteries or return to them by a single wire). Or better, a continuous current in the coil, producing a south pole below and a temporary one in the axial wire, and reversing the direction of the latter synchronously with each half-vibration of the pointer: a very convenient plan is to pass the entire current through the coil, and during its continuance divert, by means of a reverser, such portion of the current as will flow through the axial wire, and reverse the direction of that portion at the end of each half-vibration. A quantity of electricity passing through the axial wire of about four times that which circulates through the coil is a suitable proportion.

With a soft-iron wire 2·6 metres long and 1·75 mm. thick, four GROVE's cells being arranged as two attached to the coil, and eight as four to the axial wire, a single contact produced a movement of 23 mm. of the end of the pointer, and by synchronous contacts a swing of 80 centims. (or 31 inches=102 degrees), or more than a quarter of a circle, was easily obtained. [With a shorter and thinner wire and suitable helix, and the current of a NOË's thermopile of 80 elements connected as 20×4, a swing of 36 inches was produced.] The torsional movements, when first observed, were so small as to require the aid of a magnifying-glass in order to detect them; they are all attended by audible sounds in the iron.

The currents employed in these experiments being large and of low tension, the following reverser offering but little resistance was employed. Upon a wooden base were fixed four binding-screws, A, B, C, and D (Plate XLII. fig. 3). To A and B were fixed two flat and very flexible brass springs (E and F), united by a cross piece of

* Throughout this paper I call that a north pole which points to the south, and that a south pole which seeks the north.

ivory, G. To the opposite end of the base-board were also fixed by screws (H and I) two similar springs (J and K) similarly united by the ivory, L. The screw A was connected with I by a stout copper wire beneath the board; and B was similarly connected with H. To the free end of each of the four springs was attached, by means of a small screw, a vertical thick wire of platinum which projected beneath the spring for the purpose of dipping into one of two small cavities (M and N) containing mercury. The screws C and D were also provided with similar wires for dipping into the mercury.

4. *Is a magnetic metal necessary?*

I tried wires of platinum, silver, copper, lead, tin, cadmium, zinc, magnesium, aluminium, brass, and German silver, also a zinc rod 2·75 m. long and 11 mm. thick, and applied the currents in various ways, but obtained no signs of torsion. A cord of gutta percha, strained by a weight, was also subjected to the influence of the coil-current, but without effect.

5. *General cause of the torsions.*

The torsions are not due to momentary induction-currents of electricity, because they continue as long, and in many cases only as long, as the currents, and because a soldered brass tube interposed between the whole length of the coil and the axial wire did not prevent or diminish them.

The most probable cause of the phenomena appears to be the combined influence of ordinary induced longitudinal magnetic polarity and of a direction of induced magnetism at right angles to that, producing molecular motion and change of position of the particles, the two directions of induced magnetism being caused by the coil and axial electric currents respectively. We know by the alterations which occur in the length and diameter of a soft iron rod, when it is subjected to the influence of a coil-current (discovered by Dr. JOULE), and the sounds then produced in it, that a molecular movement and change of position of its particles then occur; and it appears equally certain, from the torsions and sounds produced, that whenever an electric current traverses the axis of a longitudinally magnetized piece of iron, it also causes a molecular movement and change of position of the particles.

[The phenomena may be explained upon the supposition that a coil-current lengthens an iron rod by causing the axes of its molecules to place themselves parallel to the axis of the rod; an axial one places them tangentially; and the two currents acting together place them in a direction intermediate between those two, *i. e.* in a spiral direction—the mass of the iron being in each case lengthened in the direction of the axes of the molecules, and shortened in a direction at right angles to that.]

6. *Law of direction of electrotorsion.*

It might be theoretically anticipated that the torsional movements occur in definite directions with relation to the electric currents. This has been found to be the case; and the law of the phenomenon in iron is as follows:—A. *With an axial current.* A current flowing from a south to a north pole produces a left-handed torsion, and one from a north to a south pole produces a right-handed one*. B. *With a coil-current.* A coil-current with its south pole below, circulating round a vertical rod of iron through which an electric current proceeds upwards, produces left-handed torsion, and a reverse one produces right-handed torsion, in the sense already employed *.

Each of these laws, but the latter one the most frequently, is affected in a very limited proportion of cases by the order of succession in which the currents are applied.

7. *Will a coil-current alone produce torsion?*

I passed the current from 12 GROVE'S cells through the coil surrounding the iron bar 11 mm. thick (see page 529), in each direction. In each case a very small movement of the pointer to the *left* hand (= right-handed torsion *) occurred on connecting the battery, and to the right on disconnecting it. By including the index (but not the bar) in the circuit, continued vibration could be obtained by placing the contact-screw against the right-hand side of the pointer in such a position that the vertical movement alone did not break the contact, but not by placing it at the left-hand side. Similar but smaller movements in the same direction were obtained with a thinner rod, by passing the current either way. With a thin iron wire, strained by a weight, no torsions could be obtained by such means. By employing a thin tube of soft iron 10 mm. outer diameter, having the same weight of $5\frac{1}{2}$ kilogrammes attached, much larger torsions occurred; but each of the movements in this case was to the right on connecting the battery, and to the left on disconnecting, irrespective of the direction of the current. It is probable that the difference of direction of torsion in the bars and tube was due to difference of internal mechanical strain, because I have found that twisting a bar before passing the coil-current enables that bar to exhibit small torsions; WIEDEMANN also (see note, p. 529) had previously investigated that circumstance. Torsions produced by electric currents only are reversed by reversing either of the currents, but those produced by the combined influence of a coil-current and previous mechanical twist were not.

8. *Will a parallel current produce torsion?*

I suspended an iron wire 1·7 mm. diameter, provided with the pointer, in the axis of a brass tube 2·6 metres long, the tube being in one case 11·7 mm. diameter, and in another case only 7 mm. diameter. The current from the 12 GROVE'S cells, arranged as 3, was in each case passed up the tube, also down it; but no perceptible torsion was manifested.

I substituted for the brass tube a thin one of soft iron 10 mm. external diameter, and for the iron wire a cotton-covered copper one 1·7 mm. thick, with a lead weight suspended from it to keep it straight, the pointer being attached to the tube and the

* By "right-handed" torsion, in the foregoing sentences, I mean twist in the direction of the thread of an ordinary screw; but a right-handed movement of the index (sometimes also called torsion) in all other parts of this paper means the reverse of this.

battery arranged as above. By passing the current down the wire a small movement of the index, equal to 1 mm., to the left hand occurred; and by passing it up an equal amount of movement to the right hand took place. I also repeated the experiment with a copper wire 2·75 mm. diameter; the movements produced by each first current agreed in direction with those stated above, but by each subsequent current in the same direction opposite torsions of small extent occurred. The transmission of these currents diminished the residuary magnetism of the tube if the lower end was a north pole. These results show that an axial electric current in a separate conductor inside the iron acts inductively, and produces a small amount of torsion.

9. *Production of torsion by axial currents.*

To determine if an axial current in the bar or wire itself would produce torsion, I excluded the helix from the circuit, and passed the current from 12 cells in one direction, first up the bar (of 11 mm. diameter), making several successive contacts, and then down it several times. In each case a decided torsion took place on the first contact, and the index returned a small portion of the distance on stopping the current; and feeble torsions occurred in the same direction by each after-contact, the pointer returning a similar small distance on disconnecting.

10. *Will a previous coil-current enable an axial one to produce torsion?*

The above-mentioned torsions produced by an axial current alone were, to a certain extent, dependent upon the iron being previously magnetic. To ascertain this I converted the lower end of the bar, first into a *south* pole by momentary application of the coil-current and then passed the axial current *down*wards several times, then converted it into a *north* pole and again passed the axial current *down*wards several times. I then applied the coil-current to form a *south* pole, and passed the axial current *up*wards repeatedly; and then to form a *north* pole, and again passed the axial current *up*wards. In each case the *first* application of the axial current produced a comparatively large torsion, the pointer returning a small distance on stopping the current, and each subsequent contact produced in the same direction the smaller movements already mentioned; the *large* deflections, therefore, could not be produced in the same direction without intervening reversal. The directions of movement were such that an axial current proceeding from a south to a north pole imparted a left-handed twist to the iron, and one in the opposite direction produced a right-handed torsion, as shown in figs. 1, 2, 3, 4, Class A, Plate XLII.

With the thin iron tube of 10 mm. diameter, using 12 GROVE's cells arranged as 6, I obtained much larger movements than with the bar. Both with the bar and tube the magnitudes of the torsions in opposite directions were generally alike.

It appears from these results that to produce electrotorsion freely requires the application of a coil-current and of an axial one in the iron itself, and that although the former alone only slightly twists a bar or tube of iron which has been previously subjected to mechanical torsion, or does not twist it at all if it is free from such previous strain (see p. 533), it leaves a residuary condition in the iron which renders the bar capable of being afterwards freely twisted in opposite directions by opposite electric currents passed axially through it; and the opposite magnetic polarities conferred by opposite directions of the coil-current enable an electric current passed axially in one direction through the bar to produce opposite directions of torsion. It follows from this that the direction of longitudinal magnetic polarity can be ascertained by means of the direction of electrotorsion.

As in each of these experiments with an axial current in the iron itself the *first* movement of torsion in either direction was a *large* one, and the needle only slightly returned towards zero on the cessation of the current, the temporary action of an axial current succeeding a coil one leaves an iron bar in a twisted state, and the direction of the twist is opposite with opposite directions of the axial current. The results also show that when torsions are produced by this method, detorsion is prevented by some coercive or retaining influence within the bar itself, and thus potential mechanical power becomes stored up in the iron.

11. *Magnitudes of torsions produced by axial currents.*

The actual magnitudes of the torsions produced by this method were small, and varied with the length and thickness of the iron, its degree of magnetic polarity, and the strength of the battery. With iron wires 2·6 m. long, and from 1·75 to 2·17 mm. thick, possessing weak south poles at their lower ends, alternately reversed axial currents from 12 cells arranged as 3 produced 3 to 4 mm. of movement of the end of the pointer, the pointer being 47 centims. long from its point of suspension to its extremity. With a wire 3 mm. thick, and a weak south pole below, sustained by terrestrial magnetic influence only, alternately reversed axial currents produced from 1·5 to 3·5 mm. of movement; but when these currents succeeded coil ones, the movements varied from 2·25 to 5·5 mm.: and with one 3·77 mm. thick, supporting $5\frac{1}{2}$ kilogrammes, and having a weak south pole below sustained by terrestrial influence only, alternately opposite axial currents from the aforesaid battery produced 1·75 to 1·83 mm. of movement; but when those currents succeeded coil ones, the movements varied from ·75 to 2·75 mm. The magnitudes of the torsions diminished with increase of thickness of the iron.

12. *Are the torsions related to electromagnetic sounds?*

Numerous axial currents in various series were transmitted through a wire 2·17 mm. diameter (up currents, down ones, and alternate up and down ones), and the sounds observed with the aid of a stethoscope, the circuit in each instance being completed by the mutual contact of wires, not by mercury, because of the interference of the snapping sound at the surface of that metal.

In every case a more or less distinct sound occurred at the commencement of each current, and little or none at its cessation. Those emitted by currents which succeeded others in the *same* direction, and which produced the small elastic torsions only, were more metallic, and those which succeeded currents in an *opposite* direction, and produced the large inelastic torsions, were more dull. Those produced by repetition currents in the same direction did not appear to diminish in loudness in proportion to the diminution of magnitude of the torsions. Axial currents succeeding coil ones were also tried; each yielded a feeble sound at its commencement and none at its termination. In every instance in which torsion occurred there was sound emitted, and in every case where no sound was produced no torsion took place; probably therefore the two phenomena are mutually related, and the torsion is dependent upon the cause which produces the sound.

[We know that by the passage of coil-currents alone around an iron wire, or axial currents alone through it, sounds without torsion occur; and the experiments of De la Rive (Phil. Trans. 1847, p. 40; Phil. Mag. vol. xxxi. 1847, p. 328, and vol. xxxv. 1849, p. 428) have shown that such currents produce sounds in various non-magnetic substances, and those substances do not exhibit electrotorsion (see Section 4); and as the object of this research was to examine the torsion and not the sounds, I have not investigated the latter phenomena except in such cases as they appear to be connected with the former.]

It is manifest, from a consideration of the torsions and sounds, that an electric current passed through iron in a more or less magnetized state produces a molecular movement and a change of position of its particles, and that the new position continues as long as the current. Also that, on the cessation of the current, the particles make very little movement, and return only a small extent towards their original positions, because little or no sound occurs, and only a small amount of detorsion then takes place. Also that an electric current in the opposite direction produces a similar set of changes, except that the changes are in the reverse direction.

The small detorsions which occur on the cessation of every single axial current succeeding a coil one appear to be due to the reaction of the ordinary mechanical elasticity of the metal; but that is a point I have not examined.

13. *Distribution of coil-current influence in the helix.*

In order to ascertain whether the torsional influence of the helix was less at the middle of the coil than at its extremities, I tried its effect upon an iron wire 61 centims. (=24 inches) long and 1·37 mm. diameter, in the two positions, the remainder of the axial conductor being formed of thick copper wire upon which the two currents have little or no torsional effect. The current from 12 Grove's cells was applied in the most effective way, and in the same manner in each case. A series of four torsions was produced in each position, those produced by the wire at the middle of the coil being obtained after the others; the former averaged 6·44 mm. and the latter 6·11 mm. If, therefore, a small allowance be made for the gradual weakening of the current, the degrees of torsional influence at the middle part of the coil and at its ends are about alike. The magnitudes of the torsions in each case appeared to be proportional to the length of iron within the helix.

14. *Interference of terrestrial magnetism.*

It must not be forgotten that in all these experiments terrestrial magnetism operates, and more or less influences the results; also that the iron is liable to have its residual magnetism weakened by the repeated passage of an axial current in either direction through it; and if the lower end of it is a *north* pole, the polarity is often reversed. A single contact of the battery is sufficient to remove the polarity, if the current is powerful and the iron wire a small one.

In consequence of not being able to maintain a bar or wire of iron perfectly free from longitudinal magnetism during the passage of an axial current through it whilst in a vertical position, and the difficulty of detecting minute torsions with the bar in a horizontal one, I was unable to ascertain if an axial current alone would produce torsion, by experimenting with a demagnetized iron bar at right angles to the magnetic meridian. But as the magnitudes of the torsional effects of an axial current increase with the strength of the longitudinal magnetic polarity of the iron, and opposite longitudinal magnetic polarities enable each axial current to produce opposite torsions, it is highly probable that if a vertical iron rod or wire could be maintained in as perfectly an unmagnetized state in a longitudinal direction as it can in a transverse one, an axial current alone, like a coil one alone (see p. 533), would produce little or no torsion.

15. *Will axial currents remove the residuary effect of coil ones?*

Some special experiments were made with the thin wrought-iron tube of 10 mm. diameter to determine the above question, or whether the previous application of a coil-current would enable any number of torsions in alternately opposite directions to be obtained by continually reversing the axial stream. The current from 12 cells arranged as 6 was employed, and no weight was attached to the tube.

1. *With a south pole below.*—Any number of torsions could be obtained by such means, and the longitudinal magnetic polarity of the iron was not entirely removed by many passages of the current, because terrestrial magnetism continually renewed it, and because the axial current was small in relation to the conducting-power of the tube, and therefore produced less disturbing effect upon the longitudinal magnetism.

2. *With a north pole below.*—The first two downward currents, and then two upward ones, produced movements in the normal direction, the last of these being only deficient in magnitude; but all the succeeding currents caused torsions agreeing in direction with the existence of a *south* pole below, and the longitudinally magnetic polarity, tested by means of a small compass-needle, was found reversed after several axial currents had passed.

16. *Axial currents a test of residuary longitudinal magnetism in iron and steel.*

As the electromagnetic torsions constituted a new means by which residuary longitudinal magnetism might be detected, I endeavoured to ascertain more exactly and completely the effect of repeated axial currents upon that condition. I suspended in the helix a soft-iron wire 2·6 metres long and 2·22 mm. diameter, and measured the various torsions produced by a current from 12 cells arranged as 3.

A. *After making a north pole below* by means of the battery.—The current was passed 14 times through the wire, alternately in opposite directions, commencing with an upward one. The following are the magnitudes of the several torsions, expressed in millimetres of movement of the end of the pointer (the vertical arrows indicate the directions of the axial currents, and the horizontal ones those of the movements):— 1. ↑ ← 4·0; 2. ↓ → 2·0; 3. ↑ → 1·0; 4. ↓ ← 2·75; 5. ↑ → 2·5; 6. ↓ ← 3·75; 7. ↑ → 3·75; 8. ↓ ← 4·33; 9. ↑ → 4·25; 10. ↓ ← 4·75; 11. ↑ → 4·25; 12. ↓ ← 4·75; 13. ↑ → 4·0; 14. ↓ ← 4·9. On applying a compass-needle, the lower end of the wire was found magnetically neutral at the 3rd contact, and a feeble south-pole at the 10th. On examining the directions of the torsions, it will be observed that a change took place between the 2nd and 3rd currents, the directions of those previous to that change agreeing with the existence of a *north* pole below, and of those after it with a *south* one; and on comparing the magnitudes of the movements, we find that previous to that change of polarity they diminished, and after it those of the torsions produced by the *up*ward currents increased to the 10th contact only, whilst those of the *down*ward ones increased throughout.

B. *After making a south pole below.*—Ten alternately reverse currents were transmitted, commencing with an upward one; and the following are the results:—1. ↑ → 6·5; 2. ↓ ← 8·0; 3. ↑ → 6·75; 4. ↓ ← 5·33; 5. ↑ → 5·25; 6. ↓ ← 5·5; 7. ↑ → 5·0; 8. ↓ ← 6·0; 9. ↑ → 5·25; 10. ↓ ← 5·5.

The results set down under "A" show that the north polarity was first diminished and reversed, and then the south polarity increased until a downward current produced a movement of 4·9 to the left (and was still increasing); and those under "B" show that the south polarity decreased until a downward current produced a movement of 5·5 to the left—as if in each case the iron was gradually approaching a normal magnetic state by the influence of a disturbing cause and terrestrial magnetism. These results support the hypothesis that the axial current loosens the molecules of the iron, and enables terrestrial magnetic influence to reduce the iron to its normal degree of magnetism with south polarity downwards. But assuming such explanation to be true, it is not complete, because axial currents of opposite direction leave the iron in opposite states (see p. 535). The results generally also indicate that a magnetized soft-iron bar may be rendered normally magnetic by placing it vertical, and passing alternately reversed electric currents axially through it until it ceases to show a changing degree of torsion. I have not examined whether axial-electric currents would entirely remove the ordinary longitudinal magnetism if the wire was at right angles to the terrestrial magnetic meridian.

As the torsions in these experiments with an iron wire depended upon the influence of both coil and axial currents, it is evident that the magnitude of them was limited by the weakest; and as the residual longitudinal magnetism was feeble and the axial current strong, the magnitudes of the torsions varied with the amount of that residual magnetism. Assuming that the magnitude of the first torsion was to some extent in each case a measure of the residuary magnetism, and no interfering circumstances had occurred, the magnetism left in the wire by the coil-current which produced a *north* pole below was to that left by the same strength of current after producing a *south* pole as 4·0 to 6·5; and this agrees with the fact that terrestrial magnetic influence weakens the magnetism of a vertical soft-iron wire, the *north* pole of which is below. Further investigation might perhaps disclose the exact conditions under which difference of magnitude of the torsions constitutes a true measure of residual magnetism.

Similar series of experiments were made with a steel wire 2·6 m. long and 2·16 mm. diameter; the following are the results:—

A. *After making a north pole below.*—Eighteen currents were passed:—1. ↑ ← 6·0; 2. ↓ → 5·25; 3. ↑ ← 4·0; 4. ↓ → 3·75; 5. ↑ ← 3·0; 6. ↓ → 2·4; 7. ↑ ← 2·0; 8. ↓ → 2·0; 9. ↑ ← 1·75; 10. ↓ → 1·75; 11. ↑ ← 1·5; 12. ↓ → 1·5; 13. ↑ ← 1·6; 14. ↓ → 1·5; 15. ↑ ← 1·2; 16. ↓ → 1·33; 17. ↑ ← 1·33; 18. ↓ → 1·0. No reversion of the direction of torsion or of magnetic polarity took place, and the deflections produced both by the upward and downward currents diminished throughout. The non-reversal of polarity, and the slowness of decrease of magnetism, compared with that which occurred in iron, were probably due to the greater coercive power of steel.

B. *After making a south pole below.*—Sixteen currents were transmitted:—1. ↑ → 5·5; 2. ↓ ← 6·0; 3. ↑ → 5·25; 4. ↓ ← 4·25; 5. ↑ → 4·0; 6. ↓ ← 4·0; 7. ↑ → 3·75; 8. ↓ ← 3·8; 9. ↑ → 3·75; 10. ↓ ← 3·5; 11. ↑ → 3·6; 12. ↓ ← 3·4; 13. ↑ → 3·5; 14. ↓ ← 3·4; 15. ↑ → 3·5; 16. ↓ ← 3·4.

On comparing the results of "A" and "B," we find that (as in iron) the magnetism was much more weakened when the *north* pole was below than when the south pole was beneath; this result was of course due to the influence of terrestrial magnetism. With a *south* pole below, both with iron and steel, the polarity was diminished, but more so with steel than with iron.

17. *Effect of direction of axial currents upon the residuary longitudinal magnetism of iron and steel.*

I also examined the effect of a succession of axial currents, all in one direction, using the same battery-arrangement.

A. *In a soft-iron wire* 1·75 *mm. diameter.*—1. With a *south* pole below previously produced by the coil-current, six axial currents in succession were passed *down* it. The first produced a movement of 4·75 mm. to the left hand, the second 1·25 mm., and the others gradually diminished to 0·5 mm. After restoring the south polarity by a coil-current, ten axial currents were passed *up* it. The first torsion was 6·5 mm. to the right hand, the second 1·5 mm., and the others 1·25 mm. In each of these two series the torsions after the first one were largely due to the renewal of the longitudinal magnetism by terrestrial influence. 2. With a *north* pole below, six *down*ward currents were transmitted: the first produced a movement of 3·75 mm. to the right hand, and made the lower end of the wire neutrally magnetic to a compass-needle, and the following ones yielded no movement. After restoring the same polarity by means of the coil-current, six *up*ward currents were passed: the first produced a deflection of 2·5 mm. to the *left*, and rendered the lower end of the wire a feeble south pole; the second 0·6 to the *right* hand, the 3rd 1·0 to the right, and the remainder the same.

B. *In a steel wire* 2·17 *mm. diameter.*—1. With a *south* pole below, produced by the coil-current, six *down*ward currents were first passed. The first of them produced a movement of 5·5 mm. to the left hand, and the subsequent ones yielded no torsions. The polarity was then restored by means of the coil-current, and six axial currents in succession then passed *up*wards. The first gave a deflection of 3·25 mm. to the right hand, the second ·25, and the others no movement. 2. With a *north* pole below, six *down*ward currents were first transmitted; the first of them gave a torsion of 5·5 mm. to the right hand, and the succeeding ones had no effect. After restoring the polarity as before, six *up*ward currents were passed: the first produced a movement of 6·25 mm. to the left hand, and the others had no visible effect.

The sudden cessation of torsion after the first current in steel, and the much more gradual cessation of it in iron, are quite conspicuous. The fact that the magnitudes of the first torsions, both in iron and steel, are smaller with a north pole below than with a south one, agrees with the view that the magnitude of the movements depends upon that of the residuary longitudinal magnetism.

To ascertain whether in such experiments as these some of the longitudinal magnetism remained after the first axial current had passed, although no torsion was produced by the subsequent axial currents, I transmitted through the coil (containing a steel wire) a current producing a south pole below, then passed 10 axial currents in succession *down* the wire; only the first one produced torsion. On then transmitting a current *up* the wire, a torsion occurred, proving that the magnetic effect of the coil-current still remained.

18. *Will a previous axial current enable a coil-current to produce torsion?*

To ascertain also if the previous passage of an axial current conferred upon the iron the capacity of being twisted by a coil one, I passed a current from the 12 cells in one series *up* the bar of 11 mm. diameter, then through the helix several times, making the lower end of the bar a *south* pole; then up the bar again, and then several times through the coil, producing a *north* pole; and I repeated this series of experiments, employing a current *down* the bar. In each case the *first* application of the coil-current produced a large torsional movement, the index returning a small distance on stopping the current; and each subsequent contact produced in the same direction the small movement only: the *large* deflections, therefore, could not be produced in the same direction a second time without intervening reversal. I have not examined whether the small detorsions which occur on the cessation of each single coil-current succeeding an axial one are due to the ordinary elasticity of the metal. The directions of the large and small movements are shown by figures 1, 2, 3, 4, Class B, Plate XLII.*

These results confirm the view that to produce torsion freely requires the two currents (see Section 10, p. 535), and that although each current alone will produce its own magnetic effect, neither alone will twist the bar if the iron is free from mechanical strain. They also show that, although a coil-current alone produces no torsion in an annealed iron bar (see p. 533), the previous passage of a current axially through the bar puts the iron into such a magnetic state that it becomes capable of being afterwards freely twisted in opposite directions by opposite coil-currents, and that opposite axial currents cause the iron to assume two opposite directions of such state, because they enable one direction of coil-current to produce opposite directions of torsion. The results further show that the two ends of an iron rod, wire, or tube, through which an electric current has been axially passed, possess opposite properties.

It appears also that each of the opposite longitudinal magnetic states produced by the two directions of coil-current is different from each of the conditions produced by opposite axial currents, because previous magnetization of an iron bar by a coil-current in either direction did not enable the subsequent magnetization of that bar by an opposite coil-current to produce twist, whereas the previous passage, in either direction, of an axial current through it did enable such subsequent treatment of it to produce torsion; and, further, because an axial current does not lengthen an iron bar (see p. 530), but a coil-current does; the acoustic effects of the two directions of current are also different (compare Sections 12 & 23). [All these conclusions agree with the view that the axial current imparts poleless magnetism tangentially to the outer layer of molecules of the iron, and that each of the four different directions of current imparts to the free end of the iron a different property.]

As in each of these experiments with a coil-current the *first* movement of torsion was a *large* one, and the index returned only a small distance back on cessation of the current, the temporary action of a coil-current succeeding an axial one (like that of an axial current succeeding a coil one, see Section 10) leaves an iron bar in a twisted state; and the direction of that twist is opposite with opposite directions of the coil-current. By this method, therefore, as well as by the previous one (see Section 10), detorsion is prevented by some influence within the bar, and mechanical power becomes stored up.

The results of these experiments, and of those previously described (see Section 10), show that the direction of torsion in all of them depends upon that of each of the two currents, and that it was reversed by reversing either the axial or coil-current, but not

* Some cases, apparently, of torsion in reverse directions to those of figs. 1 and 4 are described on p. 552.

by reversing both. They also prove that the directions of torsion produced by a coil-current succeeding an axial one are identical with those produced by an axial current following a coil one.

The general characters of the torsions produced by a coil-current succeeding an axial one are very similar to those produced by the reverse order of currents (see Sections 9 & 10), and indicate that both are produced by the same general cause.

19. *Magnitudes of torsions produced by coil-currents succeeding axial ones.*

The magnitudes of these torsions averaged about two fifths of those produced by axial currents succeeding coil ones. With an iron wire 2·6 m. long and 3 mm. thick, and a current from 12 cells arranged as 3, coil-currents succeeding axial ones produced torsions which varied in magnitude from 1 to 5·25 mm. of movement of the end of the index; and with an iron wire 3·77 mm. diameter, supporting a weight of $5\frac{1}{2}$ kilogrammes, the movements varied from ·5 to 1·25 mm. The magnitudes of the torsions produced by this method also diminished with increase of thickness of the iron.

20. *Influence of the order of succession of the two currents upon the magnitude of the torsions.*

To ascertain this I made four series of experiments with an iron wire 1·75 mm. diameter, supporting no weight; and employed a current from 4 cells arranged as 2 for the coil, and one from 8 cells connected as 4 for the axial wire. Twelve single currents, *i.e.* six of each, were transmitted in each series:—*1st Series.* With coil-currents producing *north* poles below, alternated with *down*ward axial ones, the torsions produced by the coil-currents were all to the right hand, and averaged 1·62 mm.; and those by the axial currents were also in that direction, and averaged 1·64 mm.

2nd Series. The same direction of coil-currents, alternated with *up*ward axial ones. The torsions produced by each kind of currents were all to the left hand; those due to the coil-currents averaged 1·60 mm. in magnitude, and those produced by the axial ones averaged 2·05 mm. The large inelastic torsions produced on changing from one series to another, one of the currents being then reversed, were of course not included in the reckoning.

3rd Series. With coil-currents producing *south* poles below, alternated with *down*ward axial ones. The coil-currents produced torsions to the right hand*, and the axial ones produced torsions to the left. The former averaged ·91 mm. in magnitude, and the latter 3·82 mm.

4th Series. With coil-currents in the same direction, alternated with *up*ward axial ones, the torsions yielded by the coil-currents were to the left hand*, and averaged ·8 mm. in magnitude, whilst those due to the axial ones were to the right hand, and their average range was 5·21 mm. The average magnitude of all the coil-current torsions in the 4 series was 1·23 mm., and of axial-current ones 3·18 mm.:

* The *apparently* abnormal direction of these torsions will be treated of subsequently (see Section 21).

this great difference was no doubt due to the much greater degree of retentive power which iron possesses for longitudinal than for tangential magnetism.

The magnitude of the torsion produced by a given current depends not only upon the kind of current which immediately precedes it, but also upon the description of current which precedes that one. An axial current in a given direction succeeding a coil one nearly always produced a greater torsion if the coil one was preceded by an axial one in the opposite direction than if it followed one in the same direction. A similar but less general result occurs with coil-currents succeeding axial ones. A series of coil-currents producing north poles below, which gave an average deflection of 1·50 mm. when preceded by upward axial currents following coil ones of *similar* direction, yielded an average torsion of 3·25 mm. when the axial currents followed coil ones of *opposite* direction (see Section 30, page 549).

Alternate coil and axial currents therefore produced the largest torsions when *both* kinds of currents were alternately reversed in direction. The torsions in general produced by alternate currents appear to be due, not only to the energy of the acting current, but also to the liberated potential energy of the residual magnetism left by previous currents.

21. *Apparently exceptional cases of torsion.*

On examining the notes of the experiments of the instances of apparently abnormal direction of torsion mentioned in Section 20, it was found that in each of the whole twelve instances detorsion and not opposite torsion alone occurred—as if the current in each case simply liberated the particles of the iron from their state of permanent twist, and allowed the pointer to return to zero. It is singular that the passage of an axial current after a coil one producing a *south* pole below enables a subsequent coil-current of similar direction thus to undo the effect of a former one, whilst no corresponding phenomenon occurs with an axial current following a coil one which produces a *north* pole (see Section 20).

22. *Effect of mechanical pull.*

When making the four series of experiments described in Section 20, I made four precisely similar series whilst a weight of 5½ kilogrammes was suspended from the end of the wire. In the 1*st Series.* With coil-currents producing *north* poles below, alternated with *down*ward axial ones, the torsions produced by coil-currents averaged ·1 mm. less, and those yielded by axial ones 1·48 mm. greater magnitude than without the weight. In the 2*nd Series.* With *up*ward axial currents, those yielded by coil-currents averaged ·15 mm. more and those by axial ones ·84 mm. less than without the weight. In the 3*rd Series.* With coil-currents producing *south* poles below, alternated with *down*ward axial ones, the coil-current torsions averaged ·03 mm. more and the axial-current ones 1·53 mm. more than without the weight. In the 4*th Series.* With *up*ward axial currents, the coil-current torsions averaged ·46 mm. more and the axial-current ones ·12 mm. more than without the weight. No instance of reversal of direction of torsion, nor even detorsion, by influence of the weight occurred. It is evident from these results that the torsions produced by alternate coil and axial currents are affected by mechanical pull, and are therefore related to the forces of cohesion (compare also Section 42).

23. *Relation of coil-current torsions to electric sounds.*

To ascertain this I employed the same iron wire &c. as before (see Section 12). Coil-currents in each direction were tried, both in succession and alternation, and coil-currents succeeding axial ones were also employed. In every instance a coil-current acting alone produced a sound, both at its commencement and termination, the former being the loudest and the latter more metallic; and by repetition of the current in the same direction the two sounds were more feeble. Coil-currents succeeding axial ones also produced sounds, both at their commencement and cessation, the former being in every case louder and more dull, and the latter feebler and more metallic (see also Section 24); and by repeating the coil-current in the same direction the two sounds were more feeble. In each case, with coil-currents alone, the louder and duller sounds accompanied the large inelastic torsions, and the feebler and more metallic ones occurred with the small elastic movements; but the sounds produced by repeating a coil-current in the same direction did not appear to be weakened in proportion to the degree of diminution of magnitude of the torsions. These results are generally similar to those obtained with axial currents (see Section 12), and similar general conclusions to those stated on page 536 may be drawn from them. (For sounds produced by simultaneous and divided currents, see Section 36, p. 555.)

24. *Does a red heat destroy residual axial-current effect?*

A soft-iron wire 1·55 mm. diameter was placed in the helix, and a series of alternate coil-currents (producing south poles below) and downward axial ones transmitted, in order to ascertain the average amount of movement produced by the coil-currents. The coil-current movements were all detorsions (see Section 21) to the right hand, and averaged 5·1 mm. Ten downward axial currents were then transmitted to impart the axial state. The wire was now heated to redness throughout its length whilst in the magnetic meridian, and allowed to cool in that position. On replacing it in the helix, and passing a single coil-current in the same direction as before, not the slightest torsion occurred, although a strong metallic sound was heard in the wire on making contact. The wire was again similarly imbued with the axial influence, then heated to redness, and cooled whilst in a horizontal position at right angles to the magnetic meridian. On again replacing it in the helix and passing a coil-current as before, a torsional movement, amounting only to ·5 mm., occurred, and a dull thud was heard in the wire on making contact. It is evident that the residuary axial-current state is destroyed by a red heat, and is but little restored by cooling the wire whilst in a direction at right angles to the terrestrial magnetic meridian.

As electrotorsion is closely related to the magnetism, cohesion, and mechanical states of the iron, and these are all profoundly affected by rise of temperature, and as it does not occur in non-magnetic metals (see Section 4), it is very probable that the torsions would be modified and prevented by heating the iron to redness during the passage of the currents. In a paper "On the Magnetism of Electrodynamic Spirals" (see Phil. Mag., Oct. 1870) I have shown that with the same electric current passing through two successive spirals of iron and copper wire, the tangential or transverse magnetism of the iron is much greater than that of the copper at ordinary temperature; but as the temperature of the two spirals is raised to full redness, the tangential magnetism of the two becomes equal.

25. *Is the axial-current state uniformly distributed?*

To examine this I employed an iron wire 2·6 m. long and 1·75 mm. diameter, and compared the magnitudes of the torsions produced in it by a current in a helix 61 centims. long surrounding the lower end of the wire, with those obtained when the coil surrounded its middle portion. The former averaged 3·1 mm. and the latter 3·2. The magnitudes of the movements, compared with those obtained with longer coils, indicated that the amount of torsion varied directly as the length of the wire within the helix.

I also strewed fine iron filings upon a thin sheet of glass lying upon a horizontal annealed iron wire conveying a strong voltaic current in a direction at right angles to the terrestrial magnetic meridian, and vibrated the glass; no unequal distribution of the filings could be detected.

26. *Retentive power of iron for axial-current influence.*

As an axial current passed through a recently annealed rod of iron or steel leaves it in a different physical state (without twisting it), and one succeeding a coil-current leaves the bar in a twisted condition, it is evident that iron possesses a retentive power, not only for the influence of a coil-current, but also for that of an axial one, and that the residuary axial-current state may exist with or without the condition of twist.

In consequence of this retentive power of iron and steel for those effects, both the direction and the magnitude of the torsions in every case depend not only upon the kind and direction of the currents being applied, and upon the condition of the rod with regard to previous mechanical strain, but also upon the state of it with regard to both those residuary influences.

27. *Will coil-currents remove the residuary effect of axial ones?*

In these experiments a soft iron wire 2·6 m. long and 3 mm. diameter was used, no weight being attached to it, and the battery of twelve cells was arranged for intensity of three.

(1) *After passage of a* down*ward current.*—Five coil-currents of alternately opposite direction were passed, the first producing a north pole below. The directions and

magnitudes of movement of the pointer were as follows:—1st, → 2·25 mm.; 2nd, ← 1·5; 3rd, → 1·0; 4th, ← 0·5; and 5th, → 0·5.

(2) *After an* up*ward one.*—Four alternately opposite currents were passed, the first producing a south pole below. The movements were:—1st, → 2·25; 2nd, ← 1·75; 3rd, → 0·5; and 4th, ← 0·5. A series of alternately opposite coil-currents, therefore, gradually removes the residual effect in an iron wire of an axial current in either direction.

On comparing these results with those described on page 538 it appears that it required more persistent treatment to remove the residual effect of a coil-current than that of an axial one, probably partly because the influence of terrestrial magnetism assisted in maintaining the former and in removing the latter.

If we assume that the first torsion in each of these two sets of experiments was, to some extent, a measure of the residuary effect of the axial current, we find that in iron the magnitudes of residuary effect of a downward axial current and of an upward one were equal.

As a series of coil-currents only gradually removes the residual effect of axial ones, and a series of axial currents only very gradually changes the ordinary magnetic polarity of iron and steel (see Sections 16 & 28), the degree of persistency of those residuary conditions must be remembered whilst making experiments in electrotorsion.

It is probable that the longitudinally magnetizing power of terrestrial magnetism, like that of a coil-current, would also remove the residual effect of an axial current if the axis of the iron was in the terrestrial magnetic meridian and sufficient time was allowed, especially if vibration was also applied.

Although it requires a *series* of alternately opposite axial currents to remove the residual effect of a coil one, and a *number* of alternately reversed coil-currents to remove that of an axial one, a single opposite coil-current, also a single opposite axial one, each of sufficient power, respectively produce those effects. It would appear from this that the two states produced by opposite coil-currents (or axial ones) are incompatible and cannot coexist, and that a coil-current acts in a more mechanically advantageous way in obliterating the effect of an opposite coil-current than in removing that of an axial one; and an axial current acts more effectively in effacing the influence of an opposite axial one than in reversing or removing that of a coil one. Further investigation of the phenomena in a mechanical aspect, and of the relations of the torsions to mechanical changes, electric sounds, expansion by heat, &c., may possibly disclose a glimpse of the relative directions of the molecular movements produced in iron by the two kinds of currents.

28. *Effect of coil-currents upon residuary axial-current influence in steel.*

These experiments were similar to those in Section 27. The wire was 2·6 m. long and 2·16 mm. diameter, and the same battery-current employed as before.

(1) *After passing a* down*ward axial current.*—Fourteen coil-currents, alternately

opposite in direction, were passed, commencing with one which produced a north pole below. The following represent the results:—1. N. → 4·0; 2. S. ← 4·0; 3. N. → 3·5; 4. S. ← 3·25; 5. N. → 2·75; 6. S. ← 2·5; 7. N. → 2·7; 8. S. ← 2·25; 9. N. → 2·7; 10. S. ← 2·0; 11. N. → 2·3; 12. S. ← 1·75; 13. N. → 2·0; 14. S. ← 1·8.

(2) *After an upward current.*—Sixteen coil-currents, the first producing a south pole below:—1. S. → 2·75; 2. N. ← 5·25; 3. S. → 4·25; 4. N. ← 3·75; 5. S. → 3·70; 6. N. ← 3·25; 7. S. → 3·25; 8. N. ← 3·10; 9. S. → 3·20; 10. N. ← 3·00; 11. S. → 3·00; 12. N. ← 3·00; 13. S. → 2·75; 14. N. ← 3·25; 15. S. → 2·83; 16. N. ← 2·88.

On comparing these results with those obtained with iron (described in Section 27), we find that the residual effect, both of a downward and of an upward axial current, was much more persistent in steel than in iron; and we may conclude that steel possesses, in a greater degree than iron, a coercive power for the influence of an axial electric current.

29. *Influence of* direction *of coil-currents upon residuary effect of axial ones.*

To determine whether coil-currents producing a north pole below had a different effect upon the residuary influence of an axial one from those in an opposite direction, I made the following experiments, using the current from twelve GROVE'S cells arranged as three:—

(A) *With a soft iron wire* 1·75 *mm. diameter.*—1st. After an *up*ward axial current from the same battery, six successive coil-currents, each producing a *north* pole below, were passed: the first produced a deflection of 2·75 mm. to the left hand, and the others no movement. After restoring the axial condition by several upward currents, six coil ones, each producing a *south* pole, were transmitted: the first produced a movement of 1·6 mm. to the right hand, and the others no effect. 2nd. After a *down*ward axial current, six coil-currents, producing north poles below, were passed: the first yielded a movement of 4 mm. to the right hand, and the remainder had no effect. The downward axial-current influence was then restored, and six coil-currents producing south poles below transmitted: the first resulted in a movement of 4·75 mm. to the left hand; the others were without effect.

On comparing these results with those described in Section 17, page 540, it will be seen that the cessation of torsion was less sudden with axial currents succeeding coil ones than with the reverse, probably because the residuary axial condition is less stable than the residuary coil one, and the latter was renewed by the influence of terrestrial magnetism.

(B) *With a steel wire* 2·17 *mm. diameter.*—1st. After an *up*ward axial current, six coil-currents, producing north poles below, were transmitted: the first produced a movement of 0·5 mm. to the left, and the others no effect. The smallness of the torsion was partly because the lower end of the wire was previously a north pole. After restoring the upward axial current several times, six coil ones, producing south poles below, were passed: the first developed a movement of 6·75 mm. to the right hand,

and the others gave only traces of effect. 2nd. After a *down*ward current, six coil ones, producing *north* poles below, were transmitted: the first gave a movement of 5·25 mm. to the right hand, and the others scarcely any effect. The downward current being restored several times, six coil ones, producing south poles below, were passed: the first produced a movement of 5·5 mm. to the left hand, and the others scarcely any effect.

These results may be compared with those obtained with the same wire and battery-current, and described in Section 17, page 540.

To ascertain whether in these cases a portion of the residual axial-current influence still remained in the steel, I passed an axial current down a steel wire in the helix, and then a series of ten currents through the coil, each producing a north pole below. The first coil one produced a movement of 3·5 mm. to the right hand, and the others only minute torsions. On now passing an opposite current through the coil, a movement of 4 mm. to the left hand took place, proving that the axial influence still remained.

30. *Relative values of residuary effects of opposite coil-currents and of axial ones in producing torsion.*

Several of the series of experiments already described have shown that the magnitude of the first torsion produced by a current is specially liable to be affected by various mechanical and magnetic conditions of the axial wire or rod, which may be very readily overlooked, and is therefore only a very crude measure of the amount of residuary effect of a previous current.

In order, therefore, to obtain more precise knowledge respecting the relative amounts of residuary effect of opposite *coil*-currents I transmitted two series of such currents, and passed, in the interval of time between each current, in the first series a momentary *up*ward axial one, and in the second series a *down*ward one; and to obtain similar information respecting opposite *axial* currents I passed two series also of them, and in the space of time between each current transmitted in the first series a momentary coil one, producing a *north* pole below, and in the second series one producing a *south* pole. In all the experiments the iron wire employed was 1·75 mm. thick, and had no weight attached to it; and the electric current was from twelve cells arranged as three.

The following are the results tabulated, and the determinations in each series numbered in the order in which they were made. The capital letters indicate the kind of polarity of the lower end of the wire, the vertical arrows show the direction of the axial current, the horizontal ones that of the movements of the index, and the decimal numbers their magnitudes; the variations in these numbers in each vertical column arose chiefly from the difficulty of getting the pointer perfectly steady. A rigid apparatus, and a firm foundation for its support, are highly necessary in cases where the torsions require to be accurately measured.

The lower end of the wire was a weak south pole at the commencement of the experiments; the pointer also was at zero, and the same zero was maintained throughout the whole of the experiments.

(A) *Residuary effect of coil-currents.—First Series.* With *up*ward axial currents, the first being preceded by a coil one, producing a north pole below:—

	↑	S.	↑	N.
	1. 2·0 ←	2. 1·25 →	3. 5·5 →	4. 2·75 ←
	5. 1·5 ←	6. 1·25 →	7. 5·25 →	8. 3·25 ←
	9. 1·75 ←	10. 1·25 →	11. 4·75 →	12. 3·50 ←
	13. 1·25 ←	14. ·75 →	15. 5·00 →	16. 3·25 ←
	17. 1·25 ←	18. 1·00 →	19. 4·75 →	20. 3·50 ←
	5)7·75	5)5·50	5)25·25	5)16·25
Averages	1·55	1·1	5·05	3·25

The largest torsions were produced by axial currents, and the smallest by coil ones; therefore the former left the smallest residual effect. Upward axial currents succeeding coil ones which produced a south pole below, gave larger torsions than those succeeding coil ones which yielded a north pole, in the proportion of 5·05 to 1·55; therefore coil-currents producing a south pole below left a larger residual effect than those producing a north pole. These two numbers exhibit a greater difference than those previously found (see Section 16, p. 539).

Second Series. With *down*ward axial currents, the first being preceded by a coil one producing a south pole below:—

	↓	N.	↓	S.
	1. 3·8 ←	2. 3·5 →	3. 3·0 →	4. ·5 ←
	5. 3·75 ←	6. 3·3 →	7. 2·8 →	8. ·5 ←
	9. 4·0 ←	10. 2·75 →	11. 2·25 →	12. ·0
	13. 4·0 ←	14. 3·5 →	15. 3·10 →	16. ·0
	17. 4·0 ←	18. 3·3 →	19. 3·75 →	20. ·0
	5)19·55	5)16·35	5)14·90	5)1·0
Averages	3·91	3·27	2·98	·2

The largest torsions were caused by the axial currents, and the smallest by coil ones. Downward axial currents succeeding coil ones which produced a south pole below gave larger torsions than those succeeding coil ones producing a north pole, in the proportion of 3·91 to 2·98.

(B) *Residuary effect of axial currents.—First Series.* With coil-currents producing a *north* pole below, the first axial one being preceded by a coil one in that direction:—

↑	N.	↓	N.
1. 1·5 ←	2. 1·25 ←	3. 3·25 →	4. 2·0 →
5. 1·75 ←	6. 1·50 ←	7. 3·25 →	8. 1·5 →
9. 2·0 ←	10. 1·50 ←	11. 3·5 →	12. 2·25 →
13. 2·2 ←	14. 1·50 ←	15. 3·25 →	16. 1·0 →
17. 1·75 ←	18. 1·75 ←	19. 3·3 →	20. 1·1 →
5)9·20	5)7·50	5)16·55	5)7·85
Averages 1·84	1·50	3·31	1·57

The largest torsions were caused by axial currents, and the smallest by coil ones. Coil-currents producing a north pole below, succeeding *down*ward axial ones, yielded very slightly larger torsions than those succeeding *up*ward ones; therefore the residual effects of downward and upward currents were not widely different: the numbers given in Section 27, page 546, agree with this result.

Second Series. With coil-currents producing a *south* pole below, the first axial one being preceded by a coil one of that direction:—

↑	S.	↓	S.
1. 5·25 →	2. 1·0 ←	3. 5·0 ←	4. 1·0 →
5. 6·25 →	6. 1·25 ←	7. 4·5 ←	8. 1·75 →
9. 6·0 →	10. 1·5 ←	11. 4·5 ←	12. 1·5 →
13. 5·83 →	14. 1·0 ←	15. 5·25 ←	16. 1·5 →
17. 6·25 →	18. 1·5 ←	19. 4·5 ←	20. 1·25 →
5)29·58	5)6·25	5)23·75	5)7·00
Averages 5·91	1·25	4·75	1·40

The largest torsions were produced by axial currents, and the smallest by coil ones. Coil-currents producing a south pole below, succeeding *down*ward axial ones, yielded torsions not much larger than those succeeding *up*ward ones; this agrees with the immediately preceding result obtained with coil-currents producing a north pole.

In these four series of experiments, axial currents succeeding coil ones which produced a south pole below, yielded larger torsions than those which succeeded the opposite direction of coil-currents, because the influence of terrestrial magnetism strengthened a residuary south pole and weakened a residuary north one. The average magnitude of all the coil-current torsions was 1·69 mm., and of all the axial-current ones 3·66 mm.

Comparison of the average numbers in these series of experiments confirms the statement already made (Section 20, p. 543), that "the magnitude of the torsion produced by a given current depends not only upon the kind of current which immediately precedes it, but also upon the description of current which precedes that one. An axial current in a given direction succeeding a coil one nearly always produced a greater torsion if the coil one was preceded by an axial one in the opposite direction than if it followed one in the same direction. A similar but less general result occurs with coil-currents succeeding axial ones." Thus:—

				mm.						mm.	mm.	
↑	N.	↑	gave	1·55,	whereas	↓	N.	↑	gave	1·84=	·29	increase.
↓	N.	↓	"	2·98,	"	↑	N.	↓	"	3·31=	·33	"
↑	S.	↑	"	5·05,	"	↓	S.	↑	"	5·91=	·86	"
↓	S.	↓	"	3·91,	"	↑	S.	↓	"	4·75=	·84	"
N.	↓	N.	"	1·57,	"	S.	↓	N.	"	3·27=	1·70	"
N.	↑	N.	"	1·50,	"	S.	↑	N.	"	3·25=	1·75	"
S.	↓	S.	"	1·40,	"	N.	↓	S.	"	·2 =	1·20	decrease.
S.	↑	S.	"	1·25,	"	N.	↑	S.	"	1·1 =	·15	"

The exceptions only occur with south-pole coil-currents succeeding axial ones (see Section 20, p. 542).

As several of the different orders of succession of currents produced torsions in the same directions, attempts were made, but unsuccessfully, to *accumulate* the torsions produced by each.

31. *Which current most determines the direction of torsion?*

The symmetry of all the torsional movements in the four immediately preceding series becomes conspicuous on classing the right-hand ones in the order of their relative magnitudes, and arranging the left-hand ones similarly; thus:—

↑	S.	↓	—4·75 ←	↓	S.	↑	—5·91 →
↓	S.	↓	—3·91 ←	↑	S.	↑	—5·05 →
S.	↑	N.	—3·25 ←	S.	↓	N.	—3·27 →
↓	N.	↑	—1·84 ←	↑	N.	↓	—3·31 →
↑	N.	↑	—1·55 ←	↓	N.	↓	—2·98 →
N.	↑	N.	—1·50 ←	N.	↓	N.	—1·57 →
S.	↓	S.	—1·40 →*	S.	↑	S.	—1·25 ←*
N.	↓	S.	— ·20 ←	N.	↑	S.	—1·10 →

As in each combination of three currents in the foregoing Table (except the two which produce torsions in an apparently abnormal direction) the first current may be omitted without altering the direction of torsion†, it is evident that the direction of torsion depends upon one or both of the remaining two; and as each combination of currents in the right-hand column would then differ from the corresponding one of the left-hand column only in having its AXIAL current in a reverse direction, it is probably the *axial* current which most determines the direction of torsion. It is, of course, possible so to arrange the different members of the Table that each member of the right-hand column

* Those marked * are apparently abnormal in direction (see Section 32).

† The first current of the three in those cases affects only the *magnitude* of the torsion.

would differ from the corresponding left-hand one only by a reverse direction of its *coil*-current; but in that case the magnitudes would be unsymmetrical.

32. *Apparently exceptional cases of torsion.*

The directions of the torsions given in the two columns headed "S" on page 550 disagree with those shown by the figures in Class B, Plate XLII. (see Section 18), and apparently contradict the law stated in Section 6. On examining the notes of the experiments they were, however, found, like those described in Section 20, page 542 (see also Section 21), to be cases not of torsion, but of detorsion; they coincide also with the instances of decrease of magnitude of movement noticed in Section 30, page 551, and Section 31. Why a coil-current producing a south pole below should behave thus in cases where it followed an axial one which was preceded by a *similar* coil one, and not in those where the axial one was preceded by a *dissimilar* coil one (see Section 30, p. 549), and why such a phenomenon does not occur with a coil-current which produces a *north* pole below (see Section 30, page 550), I have not investigated. These detorsions are, however, probably dependent upon the influence of terrestrial magnetism, because they do not occur when the south pole is *above*.

As real torsion and detorsion can only be detected and measured by the aid of a proper zero-point, it is necessary to have the wire well annealed and free from magnetism and mechanical twist before commencing a series of experiments, and not to disturb the zero-point by mechanical motion of the apparatus. A very effectual way to remove the residual effects of both coil- and axial currents is to heat the rod or wire to redness in a direction at right angles to the magnetic meridian, and allow it to cool in that position without disturbing it (see Section 24). A more convenient but less perfect way is to repeatedly and simultaneously pass a coil-current producing a south pole below, and an axial one of proper relative strength (see Section 37, page 555), and stop the two currents simultaneously; the pointer will then settle very near zero, and the wire will only possess the usual magnetism induced by terrestrial influence (see Section 35).

33. *Coexistence of the coil-current and axial-current states in iron and steel.*

The two conditions, or rather directions, of magnetic condition were observed to coexist in the same wire in many of the experiments. All rods or wires of iron or steel in which there remained the effect of an axial current were at the same time in a more or less longitudinally magnetic state by the influence of terrestrial magnetism, and could then be twisted by the application either of a suitable coil-current or of an axial one. These properties may, however, be also interpreted according to the view already given (see Section 5, p. 532), that in all wires of iron under such circumstances the axes of the molecules lie in a spiral direction with regard to the axis of the wire, and are therefore in a position to be moved by the influence either of a longitudinally or tangentially magnetizing force.

The view that the two conditions are to some extent distinct and independent agrees with the fact that a suitably powerful coil-current *at once* removes and reverses the residuary longitudinal magnetic polarity in a soft iron wire, but only gradually removes the residual effect of an axial current, and does not at all reverse it (see Section 27). Each axial current also transmits its own characteristic influence through several subsequent coil-current changes, and each coil-current similarly through axial-current changes, in a kind of hereditary manner.

34. *The condition produced in iron and steel by an axial current.*

The experiments generally described in this paper show conclusively that the magnetism produced in iron by an axial-electric current is distributed very differently from that in a cross section of an ordinary electromagnet; it also arises from an influence within the iron, whereas the latter is produced by one from without. They also show that the phenomenon of electrotorsion is essentially magnetic, and strongly support the view that the state existing in iron when an electric current is passing axially through it, upon which the torsion depends, is not the transverse magnetism of the current itself, and which is inseparable from it (see Section 24, page 545), but that induced in the iron by the current, because electrotorsion does not occur in non-magnetic metals (see Section 4), and because the residuary axial-current state is destroyed by a red heat (see Section 24).

I have not made any experiments to ascertain whether the effect of an axial current can be communicated at a distance from one piece of iron to another by mere proximity or contact; nor have I examined whether the same condition can be acquired by vibrating a demagnetized iron rod at right angles to the terrestrial magnetic meridian*.

35. *Torsions produced by simultaneous coil- and axial currents.*

Several modifications of this method were examined:—1st, with undivided currents; 2nd, with divided ones; and 3rd, with one current passed temporarily during the continuance of the other, &c.; and in each case torsions were freely produced. The second and third of these arrangements were the best.

There was a special difference between the torsions produced by alternate currents and those yielded by simultaneous ones. In the former case, on cessation of the current, the pointer only slightly returned towards zero, and the wire remained twisted (except in a limited number of special instances, see Section 20, p. 542, and Section 32); on repeating the current in the same direction, only the small elastic torsions occurred, and the large movements in the same direction could only be again obtained by reversing the current, and then again repeating it in the original direction. But with the two currents flowing simultaneously, on stopping them the index returned nearly to zero,

* About the year 1777 Beccaria noticed "that a needle, through which he had sent an electric shock, had in consequence acquired a curious species of polarity; for, instead of turning as usual to the north and south, it assumed a position at right angles to this, its two ends pointing to the east and west."—Roget's "Treatise on Electromagnetism," page 3, in 'Library of Useful Knowledge,' 1832.

and the wire did not remain twisted; on repeating the currents in the same direction, the very large torsion in the original direction was again produced; and any number of such torsions could be consecutively obtained without any intervening reversal of the currents. It is evident therefore that the coercive force or condition within the bar, which retains the iron in a twisted state after the passage of alternate coil- and axial currents, is either overcome or does not operate when simultaneous currents are employed.

As simultaneous currents produced very much larger torsions than alternate ones, and appeared to aid each other, and notwithstanding coil-currents destroy the effect of axial ones, and *vice versâ*, their influences, although dissimilar, are not contradictory, but appear to act upon the principle of "composition of forces."

The very much greater magnitude of the torsions obtained by this method was probably a consequence of the two magnetic conditions being very much stronger during the continuance of the currents than after their cessation. Not unfrequently, with an iron wire 1·75 mm. thick, the first movement of the index exceeded 25 millimetres. The torsional push is not limited to a small angle, but continues through the entire range of the largest arc through which the pointer can be made to swing, even though that exceeds one third of a circle.

36. *Torsions yielded by simultaneous and divided currents.*

With the two currents commenced together and terminated also simultaneously, the index made a very large movement at the commencement of the currents, remained considerably (though much less) deflected during their continuance, and returned nearly to zero on their cessation, provided the two currents were of proper relative degrees of strength. In all the experiments in which currents simultaneous in their commencement were employed (and they were very many), the direction of torsion agreed with the law (see Section 6), probably because such a method of applying them largely removes at once all interfering residuary influences.

Eight series of experiments, including sixty distinct and different orders of succession of currents, were made—passing simultaneous currents after single ones, both coil and axial, and single currents after simultaneous ones; employing an iron wire 1·75 mm. diameter, and currents from six cells arranged as three upon each circuit. In fifty-four of these cases the directions of the torsions agreed with the law, and the magnitudes of them agreed with the results usually obtained. In the other six, all instances in which single currents following simultaneous ones were employed, and associated only with coil-currents producing a *north* pole below, no movements took place on *making*, but small detorsions occurred on *breaking* the contact.

Although the two currents of each pair of simultaneous ones in these experiments were not of proper relative strength, the coil one being in excess, the average magnitude of all the torsions produced by a single coil-current, after repeated simultaneous ones, was only 1 mm., and by a single axial one after them was 1·5 mm. By comparing these results with those obtained by means of alternate single currents under nearly similar circumstances (see Section 20, page 542), it will be seen that simultaneous currents leave less residual effect than single ones.

Simultaneous and divided currents, on the first time of passing, produced a loud and dull sound on making contact, and a weaker and more metallic one on breaking contact, but by each repetition in the same direction the reverse, and their first passage produced louder sounds than their repetitions.

37. *Influence of relative strength of the two currents.*

As the magnitude of the torsions produced by simultaneous currents depends upon both currents, and is therefore limited by the weakest, the two currents must be properly proportioned to each other in order to produce the maximum degree of torsion. To effect that object, I have increased the strength of the axial current and decreased that of the coil one (or *vice versâ*), until, after passing and stopping the two simultaneously, a small sign of residual axial-current effect was detected by torsion produced on passing a single current through the coil only. The best proportion of the two forces, with the apparatus and iron wire (2·6 m. long and 1·75 mm. diameter) I usually employed, was the current from four cells arranged as two for the coil, and that from eight arranged as four for the axial wire. By actual measurement it was found that the electric conduction-resistance of the helix in that apparatus (see Section 1) was equal to ·309 ohm, and that of the iron wire 2·6 m. long and 1·75 mm. diameter was equal to ·137 ohm; therefore with two batteries of equal power attached to the coil and iron wire respectively, the quantity of electricity passing through the axial wire was two and a quarter times the amount of that circulating through the coil; and with eight cells attached to the axial wire and four to the coil, the difference would of course be double that amount.

The torsional effects produced by simultaneous and undivided currents passing through the bar and helix in one continuous circuit were similar to those described in Section 36, but were comparatively small, evidently in consequence of the electric power being disadvantageously applied, the axial wire requiring a relatively much greater current.

38. *Influence of metal screens.*

A brass tube 2·6 m. long and 11·5 mm. external diameter was fixed in the helix, with the soft iron wire 1·75 mm. diameter suspended in its axis, and the battery divided into two portions of six cells each. By arranging each six cells as three, and transmitting the two currents simultaneously, deflections varying from 18·5 to 23·5 mm. took place, showing that the brass tube did not materially intercept the torsional influence of the coil-current. In some similar experiments, in which a thin *iron* tube was employed instead of the brass one, diminution of torsion occurred.

39. *Torsions produced by the temporary action of one current during the continuance of another.*

Iron is extremely susceptible of being affected by an electric current, and consequently every different way of applying the two currents produces a difference of effect upon it. With the present method the current which is applied *first*, whether axial or coil, produces little or no torsion according to the residuary magnetic state of the wire; whereas the *second* one produces a very large torsion, nearly or quite as great as would have occurred if the two currents commenced together. And, generally, if one of the two currents is stopped after the other, the discontinuance of the first, whether coil or axial, is attended by a much greater degree of detorsion than that of the second. The effects were modified if a weight was suspended from the wire.

Some experiments were also made of commencing one current (A) soon after the other one (B), and continuing A a short time after B had ceased. Six GROVE'S cells arranged as three were used for one circuit, and six similar ones for the other; and the iron wire employed was 1·75 mm. diameter. Every possible combination and order of succession (eight in number) of the two currents was tried. In each case the first current produced at its commencement only a small movement, varying from 0 to 5·5 mm., and the second a very large one, varying from 20 to 27·25 mm. The current which was first stopped, whether coil or axial, produced a detorsional movement, varying in magnitude from 15 to 19·5 mm.; and on stopping the other current a further detorsion took place, varying in range from 3·5 to 6·25 mm.; the needle then settled either at zero or very near it. According to these results, and allowing a greater value to the degrees most distant from zero, more than three fourths of the torsion ceased when one only of the currents was stopped; probably this was partly a result of momentum of the recoil. The magnitudes of the torsions produced by the axial currents in these experiments varied from 25 to 27 mm., and averaged 25·5 mm.; and of those yielded by the coil-currents ranged from 20 to 27·25 mm., and averaged 23·44 mm., indicating a stronger preparatory condition produced by the coil-current and an excess of that current influence.

In two experiments of these eight, the large torsion was in an opposite direction to that required by the law (see Section 6). In one of them a coil-current producing a *south* pole below was established during the continuance of a *down*ward axial current, which had been preceded by a coil one yielding a *north* pole below in an immediately previous experiment; in the other a coil one producing a *north* pole below was commenced during the flow of a *down*ward axial one, which had followed a coil-current producing a *south* pole below in the previous experiment.

These exceptions were not instances of detorsion, but actual reversals; they were found to depend upon the residual coil-influences mentioned, and upon the successive commencement of the two acting currents, because they did not occur if the residual state was prevented (by terminating the two currents of the immediately preceding experiment simultaneously) or reversed, nor if the two acting currents were made to commence simultaneously.

The residuary state preceding these instances was not manifested by a conspicuous degree of permanent twist; in the first case that amounted to 1·5 mm., and in the second to only ·25 mm.; this, however, agrees with constant experience in the subject: a non-magnetized iron wire is not visibly twisted by a powerful coil-current (or axial one) alone, but acquires an invisible potent condition which reveals itself by torsion on the subsequent passage of suitable currents. I have not examined why these exceptions to the law occur only in cases where a *down*ward axial current is employed.

These peculiar instances, together with the various other phenomena of electrotorsion and detorsion, support the view that the molecular mechanism of iron is a complex one; they also illustrate the very great influence which the order of succession of the currents exerts in some cases, and to which attention has already been called (see Section 20, page 543).

40. *General influence of the order of succession of the currents.*

A general review of the phenomena described in this paper shows that the hereditary action and order of succession of the various currents affects the torsions in all cases; in all it affects the direction and apparently also the magnitude, in a less number of cases it causes detorsion to occur, and in a very few instances it enables torsion to be produced in the opposite direction to the fullest extent.

41. *Relative magnitudes of torsional effect of electric currents during and after their passage.*

Whilst making the experiments on the magnitudes of the torsions produced by alternate coil- and axial currents (described in Section 20), I made a series of other experiments with the same iron wire (*i. e.* 1·75 mm. diameter and without any weight attached to it) and arrangement of battery, but passing one current during the continuance of the other, for the purpose of obtaining some idea of the relative magnitudes of residuary torsional influence of the two currents to that of their torsional power during their circulation in the coil and axial wire:—

(A) *With the coil-current continuous and the axial one temporary.*—1. With *south* pole below and a *down*ward current and also with an *up*ward one. 2. With a *north* pole below and a *down*ward axial current and with an *up*ward one.

(B) *With the axial current continuous and the coil one temporary.*—1. With a *north* pole below and a *down*ward axial current and with an *up*ward one. 2. With a *south* pole below and an *up*ward axial current and with a *down*ward one.

Each single experiment was repeated. The magnitudes of the whole of the torsions varied from 19 to 24 mm., and averaged 22·4 mm. In the other experiments referred to, the average magnitude of all the torsions produced by coil-currents was

1·23 mm., and of those yielded by an equal number of axial ones 3·18 mm., and of the two collectively 2·20.

It would appear from these results that in iron the residuary torsional influence of the currents generally is about one tenth of that exerted by them during their continuance*. In steel it would be a much greater proportion in consequence of the comparative smallness of the torsions yielded by that substance with simultaneous currents (see Section 44). The general result in these cases would be considerably affected by variation of the relative strengths of the two currents, because, when alternate, the axial currents yielded torsions two and a half times the range of that yielded by the coil ones, and, when simultaneous, if one current was in excess it would only exert a part of its power effectively. To diminish this latter source of error I previously adjusted the currents as accurately as I was able in the way already described in Section 37.

42. *Effect of mechanical pull on torsions produced by simultaneous currents.*

With an iron wire 3·77 mm. thick, a current from six cells arranged as three, producing a north pole below, passed temporarily through the coil during the continuance of an upward current from a similar battery through the iron wire, produced a torsional movement of 3·5 mm. whilst a weight of 5½ kilogrammes was attached to the wire, and of 13·5 mm. in the opposite direction without the weight. As mechanical pull affects the magnitude of the torsions, both with alternate currents (see Section 22) and with simultaneous ones (see also Section 43), it is evident the weight of the pointer and its counterpoise exercised a similar effect in all the experiments.

43. *Relative magnitudes of torsions by different methods.*

The magnitudes of the torsions in all cases depended upon the advantageous application of the forces of the two currents. With an iron wire 3·77 mm. thick, supporting a weight of 5½ kilogrammes, and a current from twelve GROVE's cells arranged as three:—(A) Alternate axial currents in opposite directions gave torsional movements varying in magnitude from ·5 to 3·25 mm. (B) Simultaneous and undivided currents from the same battery-arrangement gave movements varying in extent from 1·4 to 2·25 mm. (C) Simultaneous and divided currents, the coil one being from six cells arranged as three, and the axial one from the other six connected as three, yielded movements varying from 8 to 10 mm. in magnitude. (D) Similar divided currents, the axial ones being passed temporarily during the continuance of the coil ones, the torsional movements varied in extent from 1 to 6 mm. (E) Similar divided currents, with the axial ones continuous and the coil ones temporary, the movements ranged from 0 to 9 mm., and without the weight 13 mm. In these last experiments the coil-currents produced the largest torsions, but in some former experiments (see Section 39, p. 556) temporary axial currents passed during the continuance of coil ones produced the largest. The

* As the amount of residuary axial effect is less than that of coil-influence, the proportion of the former would be less, and of the latter more, than one tenth.

weight appeared to have a strong effect in modifying and diminishing the magnitude of the torsions under the headings D and E.

44. *Comparison of magnitudes of the torsions generally in iron and steel.*

I obtained the torsions with these two substances under nearly similar conditions. The diameter of the iron wire was 3 mm. and of the steel 2·7 mm., and no weight was attached to either. The electric current was from twelve GROVE'S cells, and was applied in each of the following ways:—

1st. *Alternately reversed axial currents only*, and the twelve cells arranged as three.—The torsions obtained with iron averaged 5·4 times the magnitude of those with steel; they varied from 3·25 to 3·5 mm. with iron, and from ·5 to ·75 mm. with steel.

2nd. *Alternately reversed coil-currents.*—The movements were 2·55 times as large with the steel as with the iron; their magnitudes varied from ·5 to 1 mm. with the iron, and from 1·5 to 2·33 mm. with the steel.

3rd. *Alternate axial and coil-currents*, in every possible order.—The magnitude of the movements obtained with iron averaged 1·77 time that of those obtained with steel; those with iron varied from 1 to 5·5 mm., and those with steel from ·0 to 4 mm. Several cases of detorsion occurred in this series.

4th. *Simultaneous coil- and axial currents.*—The current from six cells arranged as three was used with the coil, and a similar current with the axial wire, and the two currents were commenced and stopped simultaneously. Every possible combination of the two currents, and every order of succession (twelve in number) of each pair of them, was tried. The movements obtained with iron averaged 2·42 times the magnitude of those produced with steel. The magnitudes of those with iron varied from 5·75 to 16·25 mm., and with steel from ·25 to 7·75 mm.

The results of these four classes of experiments show that, except with alternately opposite coil-currents succeeding an axial one, iron is much better adapted than steel for producing large electrotorsions.

[It is probable that the generally smaller torsions obtained with steel than with iron was partly due to the greater degree of mechanical resistance which that substance offers to torsion, and partly to its differences of magnetic properties and chemical composition. Electrotorsion therefore affords prospectively a new method of investigating the mechanical and magnetic properties, and the chemical composition, of magnetic metals.]

45. *Is the voltaic coil twisted during experiments of electrotorsion?*

Some experiments were made of passing currents from the twelve cells arranged as six through a loose spiral, 630 mm. long and 16 mm. outer diameter, of thick copper wire, fixed at its upper end and surrounding a fixed cylindrical rod of soft iron 640 mm. long and 10 mm. thick, the lower end of the coil being free and provided with a pointer 380 mm. long. Torsional movements amounting to 7 mm. (as well as the well-known shortening effect) occurred if the bar was in the coil, but not otherwise, and was lessened to 5 mm. if the undivided current was caused also to traverse the bar. The torsional movement did not change in direction on changing the course of the current either in the coil, the bar, or both, but in each case agreed with a diminution of diameter of the coil; it was therefore of a different kind to the phenomenon of electrotorsion described in this paper.

46. *Electrotorsion of nickel.*

A bar of nickel 60 centims. long and 19 mm. diameter was subjected to the influence of simultaneous and divided axial and coil-currents from twelve GROVE'S cells whilst in the axis of a suitable coil; but only very minute torsional movements occurred, apparently in consequence of unsuitable dimensions of the bar.

47. *Electrotorsion in telegraph-wires.*

[As nearly all the overground telegraph-wires on the surface of the earth are composed of iron, and are more or less magnetized by terrestrial magnetic influence, especially those lying in the direction of the terrestrial magnetic meridian, it is evident that on the passage of every electric current through them electrotorsional movement tends to occur.]

Note on MR. GORE'S *Paper on Electrotorsion. By* SIR WILLIAM THOMSON, *F.R.S.**

In Section 5, "General cause of the torsions," the phenomena are attributed to the combined influence of ordinary magnetic polarity and the magnetic condition of iron at right angles to that. To see precisely how this combined influence produced the results discovered by Mr. GORE, we have only to look to JOULE'S discovery of the effects of magnetism on the dimensions of iron and steel bars, and of the musical sounds consequently produced in an electromagnet every time battery-contact is made or broken. This great discovery was first described in public on the occasion of a *conversazione* held at the Royal Victoria Gallery of Manchester, on February 16th, 1842. A printed account of it is to be found in the eighth volume of STURGEON'S 'Annals of Electricity,' p. 219, and in the 'Philosophical Magazine,' 1847, first half year. The following are the chief results obtained by JOULE:—

1. When a wire or bar of iron (or steel) is alternately subjected to, and left free from, longitudinal magnetizing force, it alternately becomes longer and shorter.

2. In the same circumstances its volume remains sensibly unaltered; and therefore it experiences lateral shrinking to an extent equal to half the extension in length†.

3. JOULE verified the lateral shrinking by passing a current through an insulated

* Not read before the Society, but ordered to be printed.

† It is understood, of course, that the shrinking is reckoned in proportion to the transverse diameter, and the extension in proportion to the length, as is usual in the geometry of strains and in the theory of elasticity.

wire along the axis of a piece of iron gas-pipe*, 1 yard long, $\frac{3}{16}$ of an inch in bore, and $\frac{3}{16}$ of an inch in thickness, and found, as he anticipated, that the *length* of the gas-pipe became *diminished* when the current was instituted, and *increased* when the current was stopped.

4. Residual magnetism leaves residual changes of dimension in iron and steel of the same signs as those exhibited when magnetizing force is first applied or afterwards re-applied.

5. Longitudinal pull †, if sufficiently intense, reduces to zero the magnetic extensions and contractions; and if more intense still, puts the metal into such a state that opposite strains are produced by it. An iron or steel wire stretched vertically by a small weight becomes elongated by magnetization, but if kept stretched by a constant sufficiently heavy weight it is shortened by magnetization ‡.

Now the passage of a current along a straight iron or steel wire of circular section gives rise to poleless magnetization in circles perpendicular to the length of the wire and with their centres in its axis. Let γ be the strength of the current through the wire, reckoned of course in absolute units. If the wire be infinitely long, the resulting field of force (whether the wire be of iron or of any other metal) is fully specified by saying that the lines of force are circles in planes perpendicular to the axis and having their centres in this line, and that the intensity of the force is

$$\frac{2\gamma}{a^2} r \text{ for points in the substance of the wire,}$$

and

$$\frac{2\gamma}{r} \text{ for external points,}$$

* The bends of the insulated wire outside the gas-pipe in JOULE's experiment complicate the circumstances somewhat by superimposing upon the circular poleless magnetization, which a single straight wire along the axis of the pipe would produce, magnetization in which there is northern polarity along one semicylinder, and southern polarity along the other semicylinder of the outer boundary of the iron pipe, and fainter opposite polarities on the inner cylindrical surface. But if the wire had been continued straight for several inches outside the pipe at each end, and then carried away to the battery without ever being brought near the gas-pipe externally, it is clear that effects in the same direction, though of slightly less magnitude (by an almost infinitesimal difference), would have been observed.

† RANKINE's nomenclature regarding stresses and strains (which is consistent with HUYGHENS's celebrated *ut tensio sic vis*) ought to be carefully followed. It is therefore necessary to introduce two nouns, pull and thrust, common enough in familiar language, but not hitherto much used in the theory of elasticity, to express longitudinal forces in the directions which would elongate or shorten the bar or wire. With reference to a stretched wire we ought to talk of the pull along the wire, and ought not to use the word strain or tension to express a stretching force. The only objection to the word pull is that some people might consider it too familiar; but surely it is not a valid objection to the mathematician or philosopher that a word, the use of which enables him to avoid ambiguity in scientific statements, is already understood by non-scientific people. According to RANKINE's nomenclature we must confine the word strain to a change of dimension or figure caused by stress; thus the longitudinal strain of a wire or of a beam experiencing a pull or thrust is the (positive or negative) elongation produced by the force.

‡ Hence the "YOUNG's modulus" of iron or steel is increased by longitudinal magnetization.

where a denotes the radius of the wire, and r denotes distance from its axis. (The same description, as is now well known—thanks to the beautiful illustrations and diagrams of iron-filings by which FARADAY showed it in the Royal Institution—is approximately applicable to the field of force in the neighbourhood of a straight portion of wire conveying a current, provided no other part of the wire is near.) Hence the intensity of the magnetization of the substance is equal to

$$\mu \frac{2\gamma}{a^2} r,$$

where μ denotes the "magnetic susceptibility" * of the substance. Let now a uniform magnetizing force X be applied along the whole length of the wire. This, combined with the force due to the current through the wire, gives at any point of the substance a resultant force equal to $\sqrt{\left(\frac{4\gamma^2 r^2}{a^4}+X^2\right)}$ in a direction inclined to the length of the wire at the angle whose tangent is $\frac{2\gamma r}{a^2 X}$. The lines of force in the resultant field are therefore spirals. The wire being supposed infinitely long, the magnetization will still be poleless †, and will be everywhere in the direction of the resultant force; and its intensity will be equal to the resultant force multiplied by the magnetic susceptibility. The extension of the substance along the spiral lines of magnetization, and its shrinkage along the orthogonal spirals, to be anticipated from JOULE'S old results, give rise to GORE'S phenomena of electrotorsion.

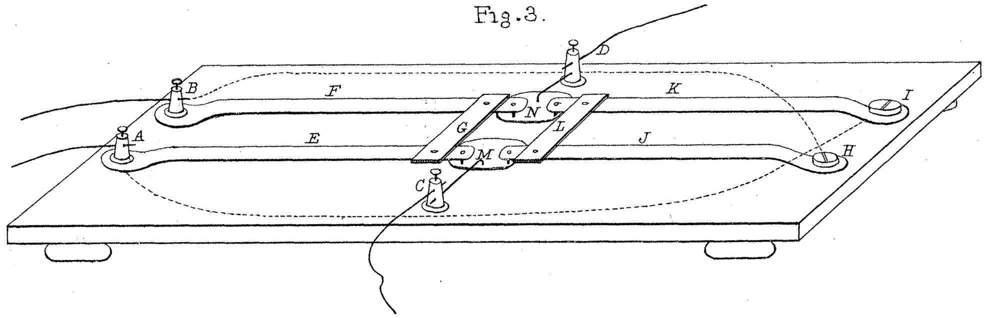
Although we thus see GORE'S "electrotorsion" as a geometrical consequence of the earlier discovery of JOULE, we must, nevertheless, regard Mr. GORE'S investigation as having led to an independent discovery of a remarkably interesting character, enhanced by the well-designed and necessarily laborious working out of varied details described in his paper.

It is difficult to conceive any physical investigation, except FARADAY'S magnetic rotation of the plane of polarization of light, more important towards a physical theory of magnetism than JOULE'S result (No. 5) above. It suggests an interesting extension of Mr. GORE'S investigation. Let the wire rod or tube experimented upon be stretched by a heavy weight, and at the same time subjected to a constant twisting-couple of sufficient magnitude, then, no doubt, the torsions as well as the elongations observed under varying magnetic influences will be the reverse of those discovered by Mr. GORE. The investigation ought, of course, to be varied by applying couple alone and longitudinal pull alone.

* THOMSON'S reprint of 'Electrostatics and Magnetism,' § 610. 3.

† The free polarity in the actual experiments due to the finiteness of the iron bar or wire and of the magnetizing helix reduces somewhat the magnitude of the effects, but does not alter their general character.

Fig. 3.



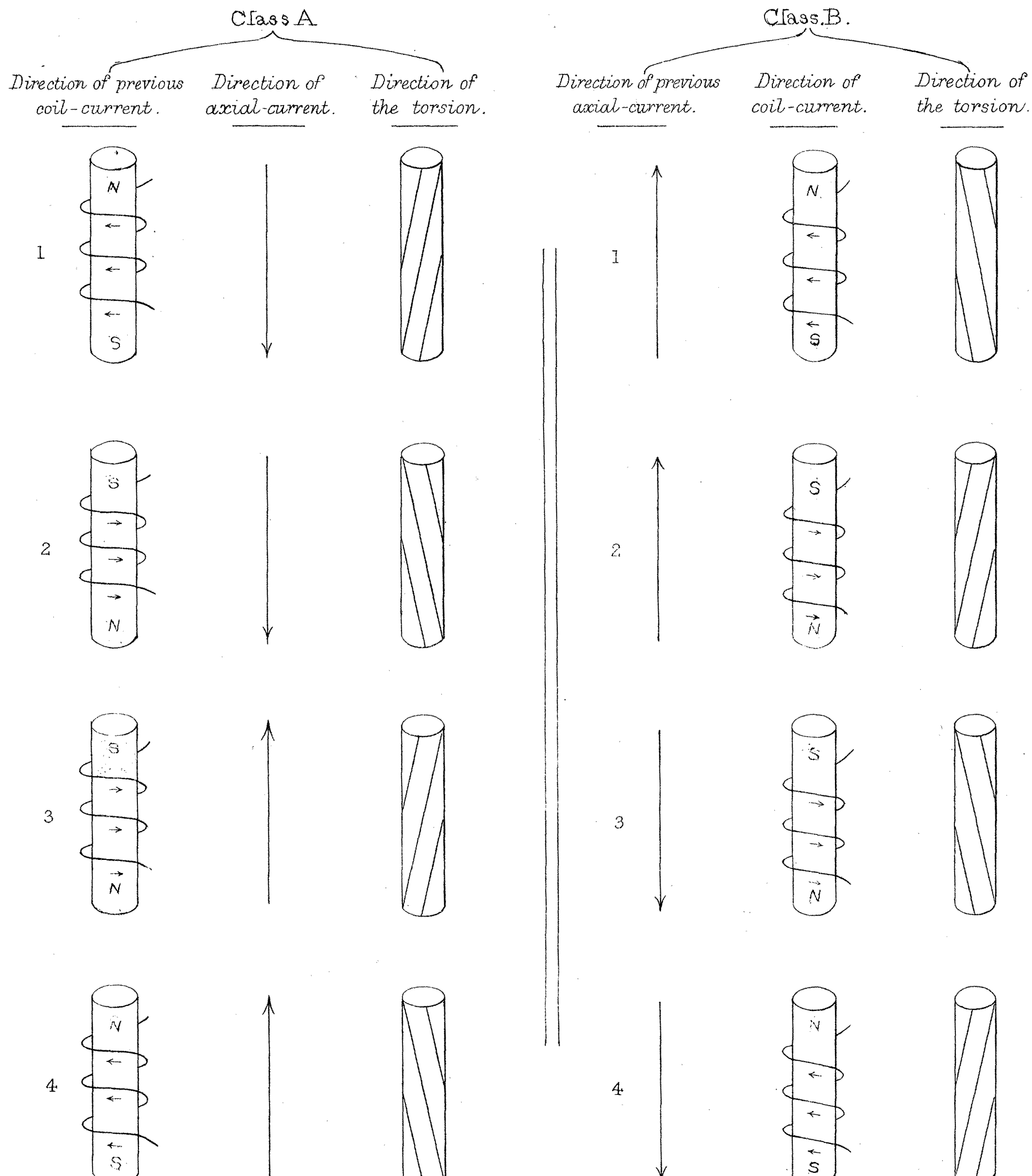
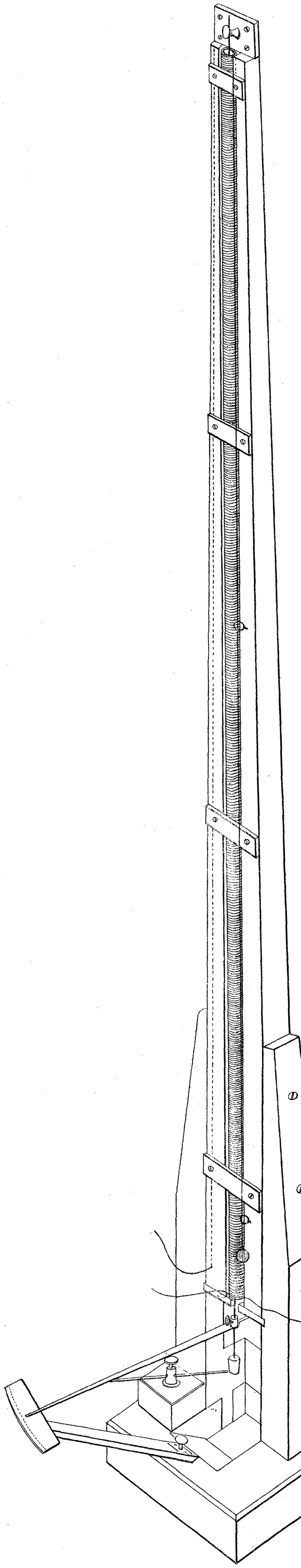


Fig. I.



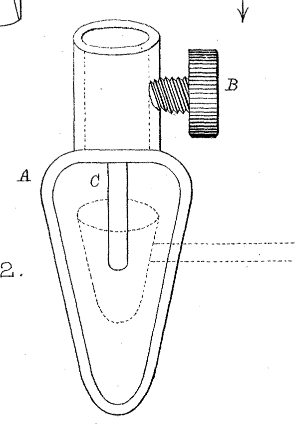


Fig. 2.