XIII. *Introductory Research on the Induction of Magnetism by Electrical Currents. By* J. P. JOULE, *F.R.S., Corr. Mem. R.A., Turin, Hon. Mem. of the Philosophical Society, Cambridge, &c.*

THE researches of JACOBI and LENZ led them some years ago to the announcement as a law, that when two bars of iron of different diameters but equal to one another in length and surrounded with coils of wire of the same length carry equal streams of electricity, the magnetism developed in the bars is proportional to their respective diameters. Experiments which I made about the same time threw doubts on my mind as to the general accuracy of the above proposition, for I found that the magnetism induced in straight bars of a variety of dimensions varying from $\frac{1}{3}$ to 1 inch in diameter, and from 7 inches to one yard in length, was nearly proportional to the length of the wire and the intensity of the current it conveyed, irrespectively of the shape or magnitude of the bars. The valuable experimental researches which have recently been made by WEBER, ROBINSON, MÜLLER, DUB and others, refer chiefly to the attraction of the keeper or submagnet, and are not calculated to confirm or disprove either of the above propositions; and the correct view is probably that of Professor THOMSON, who considers both of them as corollaries (applying to the particular conditions under which the experiments were made) of the general law, that "similar bars of different dimensions, similarly rolled with lengths of wire proportional to the squares of their linear dimensions and carrying equal currents, cause equal forces at points similarly situated with reference to them*." I have been induced to undertake some further experiments with an endeavour to elucidate the subject, and also to open the way to the investigation of the molecular changes which occur during magnetization.

I procured four iron bars one yard long and of the respective diameters $\frac{1}{6}$, $\frac{1}{4}$, $\frac{1}{2}$ and 1 inch, their weights being 1736, 3802, 14560, and 55060 grs. Each bar was wound with 56 feet of copper wire $\frac{1}{40}$th of an inch in diameter covered with silk, the number of convolutions being 1020, 712, 388, and 207 respectively. The smallest bar was closely covered throughout its entire length, but on account of the larger surface of the other bars the coils had to be distributed upon them as evenly as possible. Four other bars were also procured of the same diameters as the above. They were however twice as long, weighing 3500, 7624, 29944, and 108574 grs., and were wrapped with double the length of wire, forming 2060, 1435, 768, and 418 convolutions respectively.

* Letter to the author.

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To measure the electrical currents, I employed a galvanometer of tangents, the needle of which, half an inch long, carried a glass index over a divided circle 6 inches in diameter. This instrument was furnished with a coil of sixteen circumvolutions of 1 foot diameter, which could be exchanged for a single circle of 1 foot diameter when the intensities to be measured were very considerable. It was ascertained by experiment that the tangent of deflection by the former coil was exactly sixteen times that of the latter when the same intensity of current was employed. For convenience sake I have reduced all the observations to the latter standard; the unit current being therefore that which, passing through a circle 1 foot in diameter, is able to deflect the needle through 45°.

The amount of magnetism induced in a bar was ascertained by placing it vertically with its lower end at a distance of 6 or 12 inches from a magnetized needle $\frac{3}{16}$ths of an inch long and $\frac{1}{40}$th of an inch in diameter, suspended by a filament of silk, and having a fine glass index traversing over a graduated circle 6 inches in diameter. The force of torsion of the filament was found to be so trifling, that the tangents of the deflections of the needle could be taken as representing, without sensible error, the magnetism of the bar. Observations with so small a needle were made with great facility, the pointer moving steadily up to and attaining a new angle of deflection in eight or ten seconds after the electrical circuit was completed, the resistance of the air to the motion of the pointer being such as to prevent the smallest degree of oscillation. This resistance, however, of the air, so useful in bringing the needle speedily to rest, renders it necessary to guard carefully against any irregularity of the temperature of the case in which it is enclosed. A ray of sun-light would speedily occasion a deflection of several degrees*; and I found that the heat of the hand held over a part of the thick glass case 45° in advance of the pointer was sufficient, after penetration through the glass, to produce a current of air causing a steady deflection of no less than 30°, a deflection which subsided with extreme regularity and great slowness after the hand was removed. I would suggest that this circumstance points to the means of constructing a new and exceedingly sensible thermometer which would be valuable in many researches, particularly those on the conduction of heat.

Previously to employing electric currents, I made some experiments simply with a view to ascertain the inductive power of the earth's magnetism on the bars; and in which the action on the suspended needle was observed both at the distance of 12 and 6 inches, in order to determine the influence of distance for the convenience of future reductions. Having noticed the deflection produced by any bar, it was reversed and the observation repeated, the sum of the tangents of deflection showing the total effect produced on the magnetism of the bar by its reversion. I may here remark, that both ends of the pointer of the needle were invariably observed, though to save unnecessary detail the tangent of the mean is only given.

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* Dr. TYNDALL has drawn attention to the importance of guarding against these effects of heat on a delicately poised needle. Philosophical Magazine, 4th series, vol. iii. p. 127.

Effect of Reversal of Bars two yards long.

	Sum of tangents of deflection.	
Diameter of bar.	At 6 inches distance.	At 12 inches distance.
$\frac{1}{6}$ inch	·0450	·0088
$\frac{1}{4}$ inch	·0850	·0300
$\frac{1}{2}$ inch	·5912	·1922
1 inch	1·3910	·4598

The magnetism induced in the smaller bars appears to be nearly proportional to the square of the diameter, as might have been anticipated. The ratio of the attraction at 6 inches to that at 12 inches is 2·98.

Effect of Reversal of Bars one yard long.

	Sum of tangents of deflection.	
Diameter of bar.	At 6 inches distance.	At 12 inches distance.
$\frac{1}{6}$ inch	·0480	·0138
$\frac{1}{4}$ inch	·1260	·0384
$\frac{1}{2}$ inch	·4926	·1430
1 inch	1·0380	·3084

The magnetism induced in the smaller bars of the above set is nearly proportional to the square of the diameter; the greater amount of discrepancy arising in all probability from the inferior length of the bars compared with those of the last set. The ratio of the attractions at the two distances is as 3·39 to unity.

In the following experiments on the induction of magnetism in the above bars by electrical currents, the method employed was,—1st, to observe the magnetism of a bar under the influence of the current; 2nd, that left permanently developed; 3rd, to observe the magnetism when the current was reversed; and 4th, the magnetism remaining after the current was the second time cut off. The difference between the first and third observations gives the entire change in the magnetism of the bar consequent on the reversal of the current; the difference between the second and fourth gives the entire permanent change, or as I may term it for convenience, the *magnetic set*.

The results were obtained by using currents of four degrees of intensity, in the first two of which the needle was at 6 inches distance, in the last two at 12 inches. The latter results are reduced to the action at 6 inches distance by employing the data arrived at from the foregoing experiments.

TABLE I.

Attraction, at 6 inches, of bars one yard long wrapped with 56 feet of wire.

Diameter of bar.	Intensity of current.	Total change of magnetism by reversal of current.	Magnetic set.	Total change minus magnetic set.	Set divided by square of current.	Total change minus set, divided by current.
⅙ inch	·0044	·0164	·0014	·0150	72·31	3·409
	·0197	·1012	·0266	·0746	68·54	3·787
	·0417	·3020	·1085	·1935	62·40	4·640
	·1450	2·7747	1·7036	1·0711	81·03	7·387
¼ inch	·0041	·0364	·0038	·0326	226·05	7·951
	·0197	·2336	·0628	·1708	161·82	8·670
	·0414	·8798	·4085	·4713	238·34	11·384
	·1446	8·2871	4·9179	3·3692	235·20	23·300
½ inch	·0045	·0857	·0113	·0744	558·02	16·533
	·0194	·4573	·0882	·3691	234·35	19·026
	·0419	1·2162	·3207	·8955	182·67	21·372
	·1460	8·6948	2·7628	5·9320	129·61	40·630
inch	·0045	·1017	·0128	·0889	632·10	19·755
	·0195	·5089	·0817	·4272	214·86	21·908
	·0416	1·0935	·1377	·9558	79·57	22·976
	·1404	5·6858	1·0248	4·6610	51·99	33·198
1	2	3	4	5	6	7

Although the covered wire was fine and wound close to the iron, it could not be expected to act with exactly equal advantage in the bars of small as of large diameter, chiefly on account of the circuit taken by the wire being, relatively to the circumference of the bar, greater in the small than in the large bars. In comparing the results together, it should therefore be borne in mind, that those obtained with the bar of ⅙th of an inch diameter are somewhat diminished from the above circumstance.

A very cursory inspection of the results convinced me that the *magnetic set* followed a very different law from that which regulated the magnetic action under the influence of the current. I have therefore subtracted the former from the latter in the 5th column of the Table. Even after this separation has been effected, it will be seen from column 7 that the magnetic action over and above the set increases with considerably greater rapidity than the intensity of the current, a result which is I believe owing to a portion of the set actually existing during the action of the current being destroyed on the breaking of the circuit. It will be remarked, on inspecting column 6, that the set of the bars of ⅙ and ¼ of an inch diameter increases nearly in proportion to the square of the current, but that with the thicker bars the ratio is diminished; so that, although the set of the bars of small diameter is greater than that of the large bars when a current of powerful intensity is employed, the reverse takes place when a weak stream is used. From the 7th column it may be

gathered that the magnetism induced by an equal current, increasing at first nearly with the section of the bars, becomes ultimately almost independent of their thickness, the attractions of the half-inch and inch bars being almost exactly equal to one another.

TABLE II.

Attraction, at 6 inches, of bars two yards long wrapped with 112 feet of wire.

Diameter of bar.	Intensity of current.	Total change of magnetism by reversal of current.	Magnetic set.	Total change minus magnetic set.	Set divided by square of current.	Total change minus set, divided by current.
$\frac{1}{8}$ inch	·0042	·0150	·0009	·0141	51·02	3·357
	·0160	·0826	·0190	·0636	74·22	3·975
	·0281	·1440	·0410	·1030	51·92	3·665
	·0988	1·6531	1·0030	·6501	102·75	6·580
$\frac{1}{4}$ inch	·0042	·0451	·0037	·0414	209·75	9·857
	·0167	·2555	·0513	·2042	183·94	12·227
	·0297	·6227	·2392	·3835	271·17	12·912
	·1048	6·5007	4·3887	2·1120	399·59	20·152
$\frac{1}{2}$ inch	·0044	·0937	·0095	·0842	490·70	19·136
	·0192	·5275	·0870	·4405	236·00	22·943
	·0386	1·2243	·2597	·9646	174·30	24·990
	·1338	10·6557	4·9784	5·6773	278·08	42·429
inch	·0043	·1280	·0128	·1152	692·27	26·791
	·0178	·6088	·0822	·5266	259·44	29·584
	·0316	1·0440	·1833	·8607	183·56	27·237
	·1154	6·1017	1·6200	4·4817	121·65	38·836
1	2	3	4	5	6	7

An inspection of the above results, obtained from bars of double length wrapped with twice the length of wire, leads to conclusions similar to those we drew from Table I.

It appeared to me a matter of very great importance to investigate more closely the laws which regulate the *magnetic set*, and to determine with certainty whether the proportionality between the set and the square of the current, leading as it inevitably would to the better understanding of the nature of the molecular changes which occur in a magnetized bar, existed, and to what modifications it was subject. Seeing, therefore, that the supposed law began to fail when the thicker bars were employed, in which the mutual action of the particles distributed over a large section would naturally tend to counteract the magnetic induction developed on the exterior surface, I constructed two straight electro-magnets, one of an iron wire one yard long and $\frac{1}{25·6}$ of an inch in diameter, the other of an iron wire one yard long and $\frac{1}{17·2}$ of an inch in diameter. The former was wrapped with a single layer of covered copper wire $\frac{1}{40}$th of an inch in diameter and 21 feet long, the latter similarly with wire 27 feet long. The attractions of these wire electro-magnets were ascertained at

distances of 2 and 6 inches. They are all however reduced to the latter distance by means of the data derived from the comparison of the action of the wire electro-magnets at the respective distances.

In the adjoining Table, all the results except the last six were obtained at 2 inches distance, and the observations are divided by 8·96, the relative attraction at 2 inches to that at 6 inches, called unity: the first recorded magnetic set was deduced from the mean of thirty-six experiments on the attraction at 2 inches distance. The mean deflection amounted to no more than ·247 of a minute of a degree, and as the error incident to any single observation is from 1 to 2 minutes of a degree, it follows that no great reliance can be placed on this first result.

TABLE III.

Attraction, at 6 inches, of wire electro-magnet, $\frac{1}{25\cdot6}$ inch diameter, wrapped with 21 feet of wire.

No. of experi-ments forming the mean result.	Intensity of current.	Total change of magnetism by re-versal of current.	Magnetic set.	Total change minus magnetic set.	Set divided by square of current.	Total change minus set, divided by current.
36	·0044 } ·0065	·00072	·00001	·00071	·516 } ·934	·161 } ·159
32	·0086	·00145	·00010	·00135	1·352	·157
18	·0195	·00377	·00029	·00348	·763	·178
20	·0391	·00929	·00152	·00777	·994	·198
9	·0568	·01528	·00330	·01198	1·023	·211
8	·0787	·02657	·00782	·01875	1·263	·238
8	·0806 } ·0841	·02798	·00855	·01943	1·316 } 1·315	·241 } ·246
8	·0848	·02998	·00939	·02059	1·306	·243
8	·0870	·03220	·01001	·02219	1·323	·255
8	·0908 } ·0963	·03529	·01228	·02301	1·489 } 1·765	·253 } ·256
8	·0961	·03976	·01488	·02488	1·611	·259
8	·0992	·04570	·02090	·02480	2·124	·250
8	·0992	·04413	·01809	·02604	1·838	·262
8	·1019 } ·1060	·04573	·01904	·02669	1·834 } 2·742	·262 } ·287
8	·1046	·04838	·02047	·02791	1·871	·267
8	·1085	·05338	·02355	·02983	2·000	·275
8	·1089	·09969	·06240	·03729	5·262	·342
8	·1134 } ·1156	·05972	·02835	·03137	2·205 } 3·168	·277 } ·291
8	·1151	·10190	·06580	·03610	4·967	·314
8	·1184	·06622	·03269	·03353	2·332	·283
8	·1653 } ·1703	·14570	·09900	·04670	3·623 } 4·125	·283 } ·287
8	·1753	·19320	·14220	·05100	4·628	·291
8	·3041 } ·3043	·29710	·21420	·08290	2·316 } 2·393	·272 } ·298
8	·3045	·32810	·22900	·09910	2·470	·325
8	·4372	·38750	·24760	·13990	1·295	·320
6	1·2919	·52980	·26400	·26580	·158	·206
1	2	3	4	5	6	7

From the results of the above Table, it appears that, through the range of electrical intensities from ·0065 to ·0841, the *set* of the wire electro-magnet is proportional to the square of the current; that from the latter intensity to ·1060 the set increases with much greater rapidity, varying at one point with the 6th or 7th power of the

current; and that from the intensity ·1060 the rate of increase rapidly declines as the limit of magnetization is approached. From the last column of the Table, it will be seen that the magnetic effect of the current, separated from the set, increases very uniformly with the current, though a little more rapidly. Similar conclusions may be drawn from the results of experiments with the electro-magnet of thicker wire contained in the next Table, in which all the observations but the last four were made at 2 inches distance, and are reduced to the standard of the rest by dividing by 6·668, the observed action on the needle at the distance of 2 inches compared with that at 6 inches.

TABLE IV.

Attraction, at 6 inches, of wire electro-magnet, $\frac{1}{172}$ inch diameter, 1 yard long, wrapped with 27 feet of wire.

Number of experiments forming the mean result.	Intensity of current.	Total change of magnetism by reversal of current.	Magnetic set.	Total change minus magnetic set.	Set divided by square of current.	Total change minus set, divided by current.
44	·0043	·00213	·00007	·00206	3·786	·479
20	·0089	·00443	·00027	·00416	3·408	·469
20	·0248	·01498	·00180	·01318	2·927	·531
10	·0493	·03835	·00719	·03116	2·958	·632
10	·0900	·10720	·03611	·07109	4·458	·790
10	·1171 ⎫ ·1188	·18702	·08508	·10194	6·205 ⎫ 6·739	·871 ⎫ ·802
10	·1205 ⎭	·19404	·10560	·08844	7·273 ⎭	·734 ⎭
10	·1998	·45360	·31840	·13520	7·976	·677
10	·3448	·68450	·43310	·25140	3·643	·729
6	1·1633	1·07320	·48640	·58680	·359	·504
1	2	3	4	5	6	7

My next experiments, recorded in the following Table, were made with a bar of hard steel, $7\frac{3}{4}$ inches long, $\frac{1}{4}$ of an inch in diameter, wound with 34 feet of silked copper wire $\frac{1}{40}$th of an inch in diameter, distributed in two layers. The first five observations were obtained at the distance of 3 inches, and are reduced to the standard of the remaining observations at 9 inches by dividing by 22·762, the number of times that the attraction at 3 inches was observed to surpass that at 9 inches,

TABLE V.

Attraction, at 9 inches, of steel electro-magnet, $7\frac{3}{4}$ inches long, $\frac{1}{4}$ inch diameter, wound with 34 feet of wire.

Number of experiments forming the mean result.	Intensity of current.	Total change of magnetism on reversing the current.	Magnetic set.	Total change minus magnetic set.	Set divided by square of current.	Total change minus set, divided by current.
40	·0045	·00281	·0000092	·00280	·454	·622
40	·0089	·00543	·0000448	·00539	·566	·606
20	·0263	·01663	·0002157	·01641	·312	·624
10	·0489	·03132	·0008769	·03044	·367	·622
8	·0921	·06046	·0032278	·05723	·381	·621
20	·1594	·22992	·02356	·20636	·927	1·294
8	·3201	·65241	·17791	·47450	1·736	1·482
6	·4582	1·09119	·39722	·69397	1·892	1·514
6	·5688	1·45540	·58421	·87119	1·806	1·531
6	·8381	2·22020	1·03410	1·18610	1·472	1·415
2	1·5108	2·96510	1·29880	1·66630	·569	1·103
1	2	3	4	5	6	7

From the preceding Table it appears that the *set* of the steel bar increases almost exactly with the square of the current from the intensity ·0045 to ·0921; that thence to ·1594 it increases more rapidly than the cube of the current; and that from that point it increases in a gradually diminishing ratio as the point of saturation is approached. It will be remarked that the first five numbers of column 7 are nearly equal to one another; but that when the set begins to increase more rapidly than with the square of the current, the magnetism of the bar over and above the *set* increases more rapidly than the current.

There is a striking and instructive analogy between the phenomena above pointed out and those relating to the set and elasticity of materials. Professor HODGKINSON has pointed out that the set or permanent change of figure in any beam is proportional to the square of the force which has been applied, a law which of course is transgressed near the breaking-point. May we not with propriety term the point at which, in the foregoing experiments, the set increases so abruptly, the *magnetic breaking-point*? Mr. THOMSON has propounded the view, that the elasticity of all bodies is perfect when abstraction is made of the effect of set. The foregoing Tables indicate approximately the same law respecting what might be termed the *magnetic elasticity*. The analogy thus established between magnetic and ordinary molecular actions, when viewed in connexion with those changes of dimension which take place in iron bars by magnetization, and which I propose to study more deeply, promises to afford a point of view whence a more perfect insight into the nature of magnetism than we at present possess, may ultimately be attained.

Oak Field, Moss Side, Manchester,
    June 20, 1855.

POSTSCRIPT.

Since the above was written, I have made the subjoined experiments on the electro-magnetic attraction of contact. A cylinder of wrought iron, 9 inches long and 4 inches in diameter, had a hole 3 inches in diameter bored along its axis. The thickness of the metal of the hollow cylinder thus formed was exactly half an inch. This was cut longitudinally into two exactly equal pieces, the surfaces of which were then carefully finished. Each of these semicylinders was wound with 25 feet of covered copper wire $\frac{1}{10}$th of an inch in diameter, and making fifteen complete convolutions. One of the semicylindrical electro-magnets thus formed was firmly secured with its flat surfaces upwards; and the other, with its surfaces downwards, was suspended to the beam of a balance sensitive to 2 or 3 grains when several pounds were in each scale. A cup containing mercury was affixed to one of the terminals of the wire of the subelectro-magnet, into which a terminal of the wire of the suspended magnet dipped. And similarly, a mercury cup attached to the other terminal of the suspended electro-magnet was dipped into by a wire in connexion with the voltaic battery, so as to counteract any effect on the balance which might be produced by the other mercury cup. Each semicylindrical electro-magnet was thus acted upon by the same current of electricity, and the resulting attractions are tabulated below, each recorded number being the mean of four experimental determinations, two with the current in one direction, and the other two with it in the reverse direction.

TABLE VI.

Attraction in contact of two semicylindrical electro-magnets.

Intensity of current.	Attraction in lbs. avoirdupois.	Attraction of magnetic set.	Attraction divided by the 4th power of the current.	Attraction of magnetic set divided by the 4th power of the current.
·0410	·0365	·0045	12917	1592
·0690	·242	·0185	10676	816
·1013	1·203	·0835	11424	793
·1388	5·595	·3280	15074	883
·2074	17·937	2·5095	9694	1356
·2364	32·812	4·9685	10506	1590
·3682	not observed	17·5		952
·7013	not observed	40·25		166
1	2	3	4	5

The numbers in column 5 show that the magnetic set obtained by a weak current is nearly proportional to the square of its intensity. On inspecting column 4, it will also appear that the magnetism existing during the flow of the current follows the same law so nearly, that we may infer that it possesses the character of the magnetic set. Experiments that I have recently made on the attraction of ordinary electro-magnets for their armatures lead to the same conclusions.

December 21, 1855.