PHILOSOPHICAL TRANSACTIONS.

I. *The Influence of Stress and Strain on the Action of Physical Forces.*[*]

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Received April 5,—Read April 28, 1881.

ORIGIN AND PURPOSE OF THE INVESTIGATION.

MORE than six years ago, whilst collecting together the results of the most trustworthy measurements of the various physical constants, with a view of establishing certain relationships which I conceived to exist between them, I was much struck with the discrepancies which exist, not only between the observations of different experimenters, but also frequently between those of the same individual. Many of these discrepancies, no doubt, arise from differences in the purity of the substances employed; but, when all due allowance has been made for such a cause, there still exists a large margin, which can only be accounted for by assuming that mere alteration of molecular aggregation must modify always, and in many cases considerably, the action of physical forces. This assumption has been already abundantly justified by the experimental researches of several eminent philosophers in every part of the

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[*] In conducting these investigations I have been aided by a grant from the Government Research Fund of £4000. For this assistance, which has and will be of the greatest service to me, I here return my grateful thanks. I feel myself also under considerable obligations to Sir WILLIAM THOMSON, whose valuable paper on "The Electrodynamic Qualities of Metals" has really formed the ground-work of this memoir. The drawings have for the most part been carefully executed by Mr. J. E. JORDAN, of the Mining Record Office; and for the intelligent carrying out of the various details of the apparatus I am indebted to Mr. KIESER, of ELLIOTT Bros., and to Mr. FURSE, the Curator of the Physical Museum at King's College, London.

domain of physical science; but, though much has been done, very much more remains to be done, and a wide field lies open before us which cannot fail to richly reward the patient explorer. I write patient explorer advisedly, because, in many cases, any difference of molecular disposition which we can effect with the means at our disposal, produces only a very minute alteration in that particular physical quality which we may be examining, and an alteration which we can only hope to measure accurately by the exercise of a large amount of perseverance and conscientious labour. But whether the effect to be observed be large or small, there is no doubt that further investigations of the kind here indicated must be made ere we can gain a true insight into the nature of the action of physical forces or into any relationships which may exist between them.

I proposed to myself, therefore, to examine as far as possible each of the various physical properties of one and the same specimen of different kinds of matter; and, further, to investigate the alterations which can be produced in these properties by stress and strain; being convinced that, by so doing, much light would be thrown on such subjects as electrical conduction, magnetic induction, thermal conduction and expansion, thermo-electricity, specific heat and elasticity. The words "stress" and "strain" are here used in their widest sense as intending to denote respectively the equilibrating application[*] of *any* physical force, and the definite alteration of form or dimensions experienced thereby by the matter acted on by the force.

In furtherance of the above-mentioned objects I procured some 60 feet of wire made of each of the various metals in common use, and also of the rarer metals, silver and platinum, and of the alloy platinum-silver, the three last in a state of chemical purity, and proceeded to determine one after the other the various physical constants of each.

In consequence of the extensive scope of these researches, several of the various parts into which the paper is divided are far from being as complete as I could wish, and hope at some future period to make them; but I venture to present them as they are to the Society, as tending to show still further than has hitherto been done the "correlation of the physical forces," and the value of this mode of investigation wherein one experiment immediately suggests several others.

PART I.—MODULI OF ELASTICITY.

"YOUNG'S MODULUS."

Description of apparatus.

The values of "YOUNG'S modulus" for the various metals were determined by a method devised by Sir W. THOMSON.[†] Wires of the same material and diameter are suspended in pairs about 1 inch apart from each other, and are attached by one

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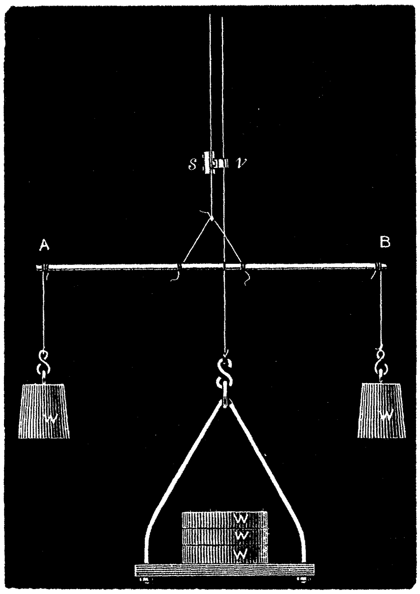
[*] 'Brit. Encyc.,' Art.: "Elasticity," p. 24.

[†] Proc. Roy. Soc., vol. xxix., p. 221.

extremity of each to the same support, the other extremities being fastened in the one case to a scale-pan, and in the other to the centre of a bar of wood or metal carrying constant equal weights at each end; the latter wire is provided with a scale, and the former with an index of some sort which, being level with and close to the scale, serves to measure any alteration of length produced by weights placed in the pan. By this simple and ingenious arrangement, any errors which might otherwise result from a slight yielding of the support, or from changes of temperature, are avoided.

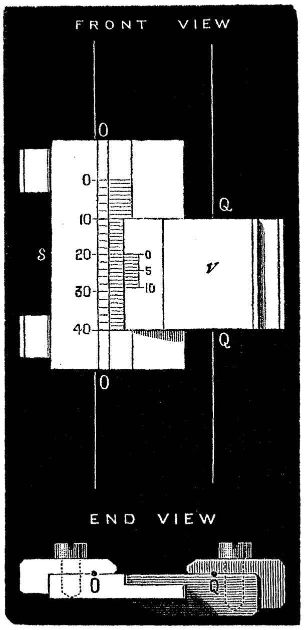
In my own particular experiments, the length of each wire between the support, which consisted of a vice firmly screwed into a stout wooden plank, and the scale and index was about 30 feet. To the extremities of the metal bar (fig. 1, A B), which was supported by one of the pair of wires, were attached two weights, each equal, in most cases, to one-fourth of the breaking-weight of the wire. To this wire was clamped by two screws a silvered metal scale (fig. 2, S), divided into half-millimetres. To the other wire was clamped in the same manner a vernier, V, reading to $\frac{1}{20}$th of a millimetre. This vernier was forked (fig. 3), so that, though capable of free up-and-down motion, it could not readily be dislodged sideways. By means of a compound microscope, an alteration of length of the wire equal $\frac{1}{100}$th of a millimetre could readily be estimated.

Fig. 1.



One-tenth size.

Figs. 2 and 3.



Scale and Vernier, full size.

Mode of experimenting.

In the case of the harder wires the one to be tested was subjected for several days to the stress produced by a weight three-fourths of the breaking-weight; the other wire, which may be called the comparison-wire, in the meantime sustaining a load equal one-half of the breaking-weight. During this time the relative positions of the scale and vernier were viewed from day to day; and when there seemed to be no alteration of these positions, the wire sustaining the heavier load was relieved from stress and allowed to rest for a period of from one to six days. Weights were then very carefully* put on to or removed from the pan attached to this wire, and the changes thereby produced in the length determined, the wire having in the meantime been permanently loaded to a sufficient extent to keep it quite straight. The softer metals—lead, tin, and even zinc and aluminium—were subjected to stresses much less in proportion to their tenacities than those used with the other metals. In their case each of the pair of wires was elongated permanently about 10 per cent. by weights, half the weight was then removed from the comparison-wire, and the two allowed to rest for four or five days. After this interval, the other wire was entirely relieved from stress, and finally was permanently loaded with a weight equal to that on the comparison-wire. As with the harder metals, the real testing did not begin till time wrought no appreciable change in the relative lengths of the two wires.

Reasons for the above precautions.

In the case of all the substances employed very great care was taken with the determinations, which often numbered more than one hundred for each of two or more different weights, and it was noticed after the experiments had been carried on for some time that the results obtained on different days frequently varied to a greater extent than could be accounted for by mere errors of observation. At first it was suspected that, in spite of the mode of suspension, a slight yielding of the upper support might be the cause of these discrepancies. Two additional wires were therefore suspended to this same support and loaded alternately with weights of 14 lbs. so as to tend to turn it about axes, respectively parallel and perpendicular to the line joining the points of attachment of the first two wires. Not the slighest effect, however, could be detected on the relative positions of the scale and vernier. The latter were then both shifted several time to parts of the wires a few inches above or below their previous positions to ascertain if any sticking between them could be observed—though in all cases care had been previously taken to adjust them so that their planes were parallel to that of the wires. But again these alterations did not seem to affect the results. The wires were now taken down and examined in case there might have

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* Several methods were tried for loading and unloading; amongst other the stress was applied by allowing measured amounts of water to flow slowly into a large but comparatively light pail attached to the wire instead of the scale-pan, the removal of the stress being accomplished by suffering the water to pass out through a piece of caoutchouc tubing attached to an orifice at the bottom of the pail, and which during the process of loading was hitched up by the side of the pail. I found, however, that quite as good results could be obtained by putting on the weights by small amounts at a time by hand; a little practice, as far as my experience goes, enables the experimenter, especially if a support be provided for the elbow, to load or unload without causing any appreciable shock.

been some slight slip of their ends through the vice. No sign, however, of anything of the kind could be detected, and on re-suspending and again testing them almost exactly the same results were obtained. Finally, the permanent loading was gradually increased in amount to determine if any error had arisen from the wires not having been sufficiently straight. It was hardly expected that this would prove to be the case, as before any of these trials had taken place the wires had been previously loaded for at least 24 hours to such an extent as to cause considerable permanent elongation. Nor indeed could any appreciable change in the measurements be detected until the weights used were such as to produce *further permanent elongation.*

When this happened, however, there was evidently an apparent alteration of elasticity. A reference to the notes made on previous occasions then revealed the fact that *whenever the above-mentioned discrepancies had occurred a similar permanent elongation had been produced.* A fresh series of experiments was therefore begun, which ended in the discovery of the following facts :—

1. In the case of a wire which has suffered permanent extension the temporary elongation which can be produced by any load becomes less as the interval between the period of permanent extension and that of applying the load becomes greater.[*]

2. This increase of elasticity is greater in proportion for great loads than for small ones.

3. The increase of elasticity takes place whether the wire is allowed to remain loaded or unloaded between the period of permanent extension and that of the testing for the elasticity.

4. The *rate of increase* of the elasticity varies considerably with different metals; with some the maximum elasticity is apparently attained in a few minutes, and with others not till some days have elapsed—iron and steel are in this last respect very remarkable.

5. The elasticity can also be increased by heavily loading and unloading several times, the rate of increase diminishing with each loading and unloading.

6. A departure from "HOOKE's law" more or less decided always attends recent permanent extension, even when the loads employed to test the elasticity do not exceed one-tenth of the breaking-weight.[†]

7. This departure is diminished very noticeably in the case of iron, and much less so with the other metals by allowing the wire to rest for some time either loaded or unloaded; it is also diminished by repeated loading and unloading.

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[*] Since writing the above I have found that the gradual increase of elasticity with time in the case of soft-iron wires has been also noticed by EWING. (Proc. Roy. Soc., 1880, No. 205, vol. xxx., p. 510.)

[†] G. WIEDEMANN and WERTHEIM have proved that there is a similar departure from "HOOKE's law" in the rigidity of metals when tested by the method of statical torsion. I shall have occasion in Part III. to refer further to Professor WIEDEMANN's valuable researches relative to torsion and magnetism: but see WIEDEMANN's 'Annalen,' 1879, vol. vi.; Phil. Mag., vol. ix., Jan. and Feb., 1880; 'La Lumière Electrique,' vol. vi., Nos. 2, 3, and 4; or WIEDEMANN's 'Galvanismus.'

The above statements apply in a greater or less degree to all the metals employed, but it will suffice perhaps to give in illustration some experiments with iron and copper wires. The pan employed in all these investigations weighed 2 kilogs., and, except in one or two instances which will be mentioned, was never detached from the wire. In the following experiments a + number will signify an increase, and a — number a decrease of length. In all cases the readings are given in half-millims., and the weight of the pan is not included in the estimate of the load.

The following series of experiments was made with an iron wire 0·62 millim. in diameter:—

Experiment I.

A weight of 12 kilogs. was put upon the pan and had the effect of permanently elongating the wire about 1½ per cent. The scale and vernier were now fixed to the wires and the following readings taken:—

No. of kilogs. on pan.	Reading of scale.	Alteration of length.	Mean values.
12	30·10		
0	5·70	−24·40	24·35[*]
12	30·50	+24·80	
0	6·20	−24·30	
8[†]	21·18		
0	5·08	−16·10	16·10
8	21·15	+16·07	
0	5·02	−16·13	
4	13·00	+ 7·98	7·95
0	5·08	− 7·92	
4	13·02	+ 7·94	

It appears therefore that the first 4 kilogs. would produce an alteration of 7·95, the second four of 8·15, and the third four of 8·25 divisions of the scale.

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[*] The + numbers are never taken in estimating the mean of the values of the alterations produced by the largest weight, in order to avoid the effect of permanent set.

[†] Scale slightly shifted by accident.

Experiment II.

The same wire having been elongated by traction to the extent of 29·4 centims. was again tried with the same weights immediately afterwards.

No. of kilogs. on pan.	Reading of scale.	Alteration of length.	Mean values.
8	21·10		
0	3·58	−17·52	17·52
8	21·10	+17·52	
0	3·58	−17·52	
4	12·08	+ 8·50	8·50
0	3·58	− 8·50	
12	31·10	+27·52	26·90
0	4·20	−26·90	
The scale-pan was now removed for 1 minute and then put on again.			
12	30·10		
0	3·12	−26·98	26·98
8	20·50	+17·38	17·37
0	3·15	−17·35	
4	11·60	+ 8·45	8·45

Taking only the last trials we see that, now, the first 4 kilogs. produce an alteration of 8·45, the second of 8·92, and the third of 9·61.

Experiment III.

The wire was still further lengthened by 11·8 centims. and the pan being on the reading of the scale was 3·40. The pan was then removed for one minute, and afterwards replaced, scale now 2·40. Again the pan was removed for 30 minutes, and replaced, scale 2·18. The trials were then renewed with the same weights as those used in the other experiments.

No. of kilogs. on pan.	Reading of scale.	Alteration of length.	Mean values.*
0	2·18		
4	10·80	+ 8·62	8·48
0	2·32	− 8·48	
8	20·30	+17·98	17·65
0	2·65	−17·65	
12	30·90	+28·25	27·50
0	3·40	−27·50	
4	11·90	+ 8·50	8·50
8	21·00	+17·60	17·50
0	3·50	−17·50	
12	30·90	+27·40	27·30
0	3·60	−27·30	

Taking the results of the last observations we obtain for the first 4 kilogs. an alteration of 8·50, for the second four 9·00, and for the third 9·80.

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* In this and the following tables the − numbers only are taken, because it was always found that after the wire had been entirely relieved from stress a small sub-permanent set was produced by each of the weights when put on for the first time after such a release.

Experiment IV.

The wire having been left for two days without weights or scale-pan was again tested with the pan on.

No. of kilogs. on pan.	Reading of scale.	Alteration of length.	Mean values.
0	3·30		
4	11·58	+ 8·28	8·23
0	3·35	− 8·23	
Scale-pan removed for 1 minute and then replaced.			
0	3·30		
8	19·80	+16·50	16·42
0	3·38	−16·42	
Pan again off and on.			
0	3·30		
12	28·10	+24·80	24·70
0	3·40	−24·70	
Pan off and on.			
0	3·30		

Here we see that the effect of the first 4 kilogs. is represented by 8·23, the second four by 8·19, and the third by 8·28.

As it had been found by preliminary experiment that the density of the wire was not permanently decreased to any extent which would introduce an appreciable error by supposing it to remain constant, we can easily make the different experiments comparable with each other by assuming that the permanent change of section is proportional to that of the length. If we do so we arrive at the following results:—

No. of experiment.	Temporary alteration of length produced by the load.	Load in kilogs.	Average alteration per 4 kilogs. on unit of area.*	Mean alteration per 4 kilogs. in each experiment.
I.	7·95	4	7·95	8·04
	16·10	8	8·05	
	24·35	12	8·12	
II.	8·16	4	8·16	8·41
	16·81	8	8·41	
	26·01	12	8·67	
III.	8·11	4	8·11	8·38
	16·70	8	8·35	
	26·05	12	8·68	
IV.	7·85	4	7·85	7·84
	15·66	8	7·83	
	23·56	12	7·85	

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* The unit of area is supposed to be that of the section of the wire in I.; the length tested was the same in all the experiments.

Remarks on the preceding experiments.

It appears from the last table that the temporary elongation produced in an iron wire by a load of given magnitude becomes greater as the permanent elongation becomes greater up to a certain limit of the latter, which limit seems to depend upon the load used to produce the temporary effect. When the above-mentioned limit has been reached further permanent elongation begins to increase the elasticity, and this increase, as other experiments have shown, is continued up to the breaking point of the wire.

The increase of elasticity produced by rest, which is very conspicuous when we compare III. and IV., is the more remarkable as it is not attended, as was at first supposed would be the case, by any appreciable permanent shortening; the latter amounting in the present instance to only ·1 millim. out of a length of 8600, actually not ·002 per cent.

This phenomenon is moreover evidently closely allied with one noted by BOTTOMLEY,[*] who has recently discovered that in the case of iron the permanent elongation which can be produced by any weight may be very largely diminished by putting on this weight in small quantities at a time with intervals of rest between, and also that the breaking stress may be considerably increased by the same process.

We may assume that the mutual attraction existing between the molecules of a wire will always tend to make them take up such positions as will give a maximum mutual attractive force. When, therefore, a wire has been permanently stretched, the molecules would immediately take up these positions were it not for coercive force; this, however, causes delay, so that if the wire were tested shortly after the permanent extension has taken place, the elasticity would be found to be less than when the molecules have had sufficient time to finally settle themselves. Nor is it necessary that any appreciable permanent contraction of the wire should attend this increase of elasticity, as the mere change of arrangement of the molecules would suffice for the purpose. To a similar cause is no doubt also due the increase of portative power which can be produced in a permanent magnet by gradually increasing its load.

Another point to be noted is the sub-permanent set which is produced in all wires; this set is greater, according as the load permanently left on the wire is greater, and also increases up to a certain limit with the time during which the stress producing the set is applied: from this it follows that the readings taken on loading a wire step by step to a certain amount will be different from those taken at the same stages of stress on unloading. This fact has already, I believe, been noticed by THOMSON; but as I wish particularly to draw attention to it in the case of iron, I give the results of one out of several experiments made on iron and copper with a view of testing the matter.

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[*] Proc. Roy. Soc., vol. xxix., p. 221.

Experiment V.

Annealed iron wire which had been very heavily loaded and unloaded a great many times on different days previous to this last experiment.

No. of kilogs. used for load.	Scale reading on loading by 4 kilogs. at a time.	Scale reading on unloading by 4 kilogs. at a time.	Difference.
0	21·22	21·22	·00
4	18·10	18·00	·10
8	15·20	15·01	·19
12	12·38	12·10	·28
16	9·45	9·22	·23
20	6·50	6·50	·00

This last experiment shows very clearly that the wire does not recover itself until all the load has been removed. Also in Experiment IV. we see that a certain amount of set disappears even with the removal of the comparatively small load of the scale-pan.

With most of the other metals the recovery of elasticity is much less marked after the first hour than is the case with iron.

The following experiments were made with a soft copper wire ·81 millim. in diameter and 630 centims. in length:—

Experiment VI.

The wire was loaded for a few minutes with a weight slightly over 8 kilogs., and, on the removal of stress, the following observations were made :—

No. of kilogs.	Time after permanent elongation.	Reading of scale.	Alteration of length.
8	4 minutes	5·80	
0	6 „	19·45	−13·65
8	8 „	5·95	+13·50
0	10 „	19·10	−13·15
8	12 „	5·80	+13·30
0	14 „	18·80	−13·00
8	16 „	5·75	+13·05
0	18 „	18·70	−12·95
8	20 „	5·68	+13·02
0	22 „	18·60	−12·92
8	17 hours	5·65	
0	17 hours 2 minutes	18·50	−12·85
8	„ 4 „	5·60	+12·90

A great part of the gradual increase of elasticity here observed is due to loading and unloading, and a similar effect may be observed in Experiments II. and III., but part is evidently due to the influence of mere rest; this is best shown by taking the differences between consecutive + or — alterations for the different times.

It will also be observed that the + and — values both here and in the experiments on iron gradually become equal under the influence of rest and loading and unloading.

Cases of aluminium and zinc.

With these metals* both the maximum temporary increase of length, caused by putting on weight, and the recovery on the removal of stress, are attained slowly in comparison with most metals. An illustration of this is afforded in the next experiment, which was made on an aluminium wire.

Experiment VII.

No. of kilogs.†	Reading of scale.	No. of minutes after putting on or taking off load.	Alteration of length in half-millims.
0	1·4		
6	18·9	1·7	+17·5
	19·2	3·0	+17·8
	19·5	5·0	+18·1
	19·8	8·5	+18·4
	20·1	12·0	+18·7
	20·4	18·0	+19·0
	20·7	26·3	+19·3
	20·8	30·0	+19·4
0	4·4	·5	−16·4
	3·7	1·5	−17·1
	3·4	6·0	−17·4
	3·0	25·0	−17·8
	1·9	1440·0	−18·9
6	19·0	1·0	+17·1
	19·3	3·0	+17·4
	19·6	5·0	+17·7
	19·9	10·5	+18·0
	20·2	18·0	+18·3
	20·5	26·0	+18·6
	20·8	40·0	+18·9
	21·1	52·0	+19·2
	21·15	60·0	+19·25
0	4·35	1·0	−16·80
	3·00	30·0	−18·15
	2·20	1440·0	−18·95

It must be observed that during the whole of this time the comparison-wire was loaded with a permanent weight equal to that on the wire which was being tested,

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[*] Probably tin and lead if they had been loaded sufficiently would have also behaved in this manner; it was impossible, however, to use any but very light weights in determining their elasticity, as otherwise permanent set would always have been produced.

[†] A weight of 4 kilogs. was kept permanently on the scale-pan.

and that the stress thus produced had been acting for several days previous to these trials.

When lesser weights were now used and only the scale-pan left on permanently the maximum alterations took place much more quickly, and the departure from "HOOKE's law," which had before been very considerable, became comparatively slight.

The modulus was calculated from these last results.

Cases of tin and lead.

These metals are remarkable for the manner in which they run down under the influence of the slightest stress, and also for the persistence of this running down; in this latter respect they surpass aluminium and zinc. It was necessary, therefore, to keep them loaded for many days before attempting to determine their elasticity. The weights also employed for this latter purpose were very small, and, in consequence, the values of the modulus obtained by using them cannot be considered as accurate as those of the other metals; I believe, however, that they are correct within 2 per cent.

"HOOKE's LAW."

We have seen that there is a very appreciable departure from this law shortly after permanent extension has taken place; but a departure also exists when a long rest has been allowed, both when the wire has in the meantime been heavily weighted and when it has not, even though only moderate loads be employed.

Thus, in the case of a soft copper wire capable of bearing a load of 18 kilogs., and which had been heavily loaded and frequently tested during a period of three weeks, the following observations were made :—

Experiment VIII.

Number of kilogs. in load.	Average alteration per kilog.
	Millimetre.
2	·808
4	·811
6	·816

The values here recorded are the means of about 20 observations on each weight made during the last three days of observation, and show small but decided differences.

Again, another piece of copper similar to the above was treated in the same manner, but for a period of six days, and when examined on the last day, with loads up to 12 kilogs., gave the following results as the means of seven trials with each weight :—

Experiment IX.

Number of kilogs. in load.	Average alteration per kilog.
	Millimetre.
2	·830
4	·835
6	·840
8	·847
10	·866
12	·911

It is here seen that the alteration per kilogramme rapidly increases when the loads become heavy, and yet in both these last experiments the wire recovered its original length on the removal of the load. It is evident, therefore, that in the case of annealed copper the length increases in greater proportion than the load, and this was proved to be the case whether the wire was allowed to rest loaded or unloaded.

Similar results were obtained with annealed platinum, silver, aluminium, platinum-silver, German-silver, and zinc. With soft iron, however, the case is different if the wire be weighted for some time after permanent extension has taken place. An examination of Experiment XIII. shows that under these circumstances the average alteration decreases up to a certain point as the load increases.

It remains now to consider the case of iron allowed to rest unloaded.

Experiment X.

An annealed iron wire, after having been permanently elongated by traction about 8 per cent., remained unloaded for several days, and was afterwards tested with weights up to 10 kilogs. :—

Number of kilogs. in load.	Alteration of length per kilog.
	Millimetres.
1	1·350
2	1·355
3	1·367
4	1·376
5	1·386
6	1·388
7	1·386
8	1·389
9	1·392
10	1·394

Here the average alterations of length increase with the load, though not to the same extent as with copper.

In both the last experiments with iron the recovery of the wire after the removal of the stress was so perfect that the zero position of the vernier was not shifted one-tenth of a millimetre.

DISCUSSION OF WERTHEIM'S EXPERIMENTS ON ELASTICITY.*

The values of "YOUNG'S modulus" obtained by WERTHEIM by vibrations, longitudinal or transverse, are generally larger than those got by static extension; and these differences are considerably greater than those which would be produced by the heating and cooling effects of contraction and elongation.

Sir W. THOMSON says† that "it is probable that his (WERTHEIM'S) moduli, determined by static elongation, are minutely accurate; the discrepancies of those found by vibrations are probably due to imperfections of the arrangements for carrying out the vibrational method." I venture, however, to believe that the main cause of the above-mentioned discrepancies is to be found in WERTHEIM'S *mode of proceeding* when determining the elasticity by *static extension.* The plan adopted by him was to put on a weight, take a reading with the measuring microscope, and, after removing the weight, take a second reading, the difference between these two readings being used in determining a value for the modulus. The same operations were repeated with greater and greater loads until the wire underwent very considerable permanent extension, and was in many cases broken. The mean of all the values thus obtained was taken to represent the true one.

Now, if, after considerable extension had taken place, WERTHEIM had repeated his trials with each of the previous weights, he would have obtained appreciably different values, and the general result would have been to give him a greater mean value for the elasticity. Moreover, my experiments have shown, as we have seen, that, even if all precautions be taken, different loads will give different values for the elasticity.

The best way of comparing the methods of static extension and longitudinal vibrations would be to determine, first, the elasticity by the former method with small loads, and then to use the latter method with the same wire under as nearly as possible the same conditions of tension. I hope at some future time to be able to make further experiments in this direction; but in some few trials with copper, iron, steel, and German-silver I have obtained values for the elasticities by the two methods which accord more nearly with each other than those got by WERTHEIM.

In order to ascertain whether the influence of rest—which in iron is so marked in increasing the value of "YOUNG'S modulus" as determined from static extension—would be equally or at all apparent when longitudinal vibrations are employed, several experiments were made on iron by the latter method, both the syren and APPUNN'S tonometer being employed for the purpose of counting the number of vibrations. Both these instruments gave very consistent results, and could be depended upon within at least $\frac{1}{2}$ per cent.; yet no difference could be detected between the note of the wire after recent permanent extension and that after a rest of 24 hours. As it was thought that perhaps the act of vibrating the wire might immediately produce the

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* Ann. de Chim. et Phys., tom. xii., 1844.

† 'Brit. Encyc.,' Art.: "Elasticity," § 77.

same effect as continued rest, a fresh pair of iron wires were suspended and tested in the usual manner with the scale and vernier; but it was ascertained that vibrating a wire under these circumstances did not produce any immediate appreciable effect on the elasticity. It would appear, therefore, that the effect of rest is not felt when the temporary elongations are very small.

PERMANENT ALTERATION OF ELASTICITY PRODUCED BY PERMANENT EXTENSION.

Experiment XI.

The same wire as in Experiment X. was further lengthened by 7, 15, 10 and 7½ centims. respectively on four separate occasions, and after each elongation the load was removed, and a rest of 24 hours allowed. After each rest the temporary alteration of length produced by 8 kilogs. was determined, the vernier after each permanent extension having been shifted to its original position.

Actual alteration observed.	Calculated alteration which would be produced on wires of the same section as in Experiment V.	Total percentage of permanent extension produced before testing.
12·88	12·88	4·0
13·02	12·87	5·1
13·32	12·87	7·5
13·50	12·84	9·0
13·65	12·83	10·2

These results are the means of several observations in each case, and show that the elasticity of copper is very slightly increased by these particular amounts of permanent extension, when the wire is allowed to rest unloaded.

A similar effect was proved to be produced on copper wire which was kept loaded for some time after permanent extension.

Experiment XII.

A piece of annealed iron wire, 860 centims. in length, was elongated by traction to the extent of 21·7 centims. so as to make it perfectly straight, and afterwards allowed to rest unloaded for two days; a set of experiments was then made which resulted in giving a mean value of 8·28 half-millims. as the alteration produced by the first 4 kilogs., 8·23 for the second, and 8·29 for the third, and an average on the whole of 8·27 for 4 kilogs.

The wire was now further lengthened by 13·3 centims., and the vernier shifted so that the same length of wire as before was under examination, and again a rest of two days allowed. On loading the wire with the same weights as before, an alteration of 8·50 was produced by the first 4 kilogs., 8·48 by the second, and 8·50 by the third, giving an average alteration of 8·49 for 4 kilogs. Allowing for the permanent diminution of section, the last alteration would correspond to 8·36 for 4 kilogs. on a wire of the same section as that previous to the second permanent elongation.

We have, in the case of this wire, therefore, a small but decided *diminution* of elasticity produced by *this amount* of permanent extension, when the wire is allowed to rest *unloaded* after the extension has taken place.

Experiment XIII.

An annealed iron wire of the same length as the previous one was tested in the same manner, except that after each permanent extension it was loaded with a weight of 20 kilogs., and this load was suffered to remain on the wire for 24 hours.

Total percentage of permanent extension ..	1·0	4·9	8·0	8·9*
Load in kilogs.	Average alteration of length in half-millims. per load of 2 kilogs. on unit area.†			
2	1·590	1·571	1·554	1·522
4	1·579	1·571	1·514	1·516
6	1·557	1·557	1·510	1·494
8	1·544	1·545	1·504	1·497
10	1·540	1·537	1·502	1·484
12	1·539	1·529	1·495	1·482
14	1·543	1·525	1·486	1·482
16	..	1·515	1·490	1·477
18	..	..	1·492	1·477
20	..	..	..	1·476

It appears, therefore, that in the case of annealed iron the elasticity is *increased* by permanent extension if the wire be allowed to remain heavily loaded for some time after such extension has taken place.

Moreover, it is remarkable that when the wire has been treated in the above-mentioned manner the average alteration per unit load *diminishes*‡ as the load

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* The wire was broken at a point about 3 inches from the scale-pan by this last extension.

† The unit area is assumed to be the area of the section of the wire after the last permanent extension; this area was ·00137 square centim.

‡ [Note added April, 1882.—It should be stated here that a load of about 6 kilogs. (not included in the loads given) was left permanently on the wire. I have since found by an indirect method (see Part II.) that, if the wire be entirely relieved from stress before beginning to test for the temporary effect of loading, the temporary elongation increases with the first few loads in greater proportion than the latter. We may say, therefore, that in the case of iron wire which has suffered very considerable permanent extension and afterwards been allowed to rest for some time either unloaded or loaded, the ratio of the temporary elongation to the load producing it first increases with the latter to a certain limit, then diminishes to a second limit, and finally begins to increase again. If, however, the wire has during the interval of rest been heavily loaded, the first limit is reached more quickly than is the case when the wire has rested unloaded; so that if, as in this instance, it is necessary to leave even a comparatively small

employed for testing *increases*, whereas with all the other annealed metals similarly treated, exactly the opposite effect is produced. This peculiarity of iron is no doubt to be attributed to its superior coercive force; and to the same cause must probably be assigned the difference between the effect of permanent extension on the elasticities of iron and copper when these metals are allowed to rest unloaded after the extension has taken place.

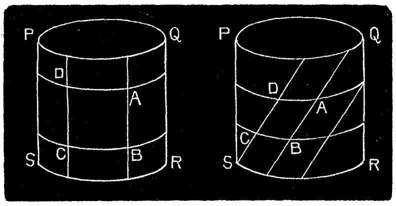
In order to examine still further the effect of leaving a heavy weight on the wire for long periods, 20 kilogs. were, after the above experiments had been made, left on the wire for one day, and then for two more days. The average increases per 2 kilogs. after each of these periods, when tested with 20 kilogs., were respectively 1·474 and 1·475 half-millims. Therefore the full effect of the loading must have been produced during the five days on which the previous trials had been made.

Finally, it should be observed that during the whole of these last experiments the wire returned to its original length on the removal of the load.

Effect of Permanent Torsion combined with Traction.

The above are the only *direct* experiments which were made of the effect of permanent extension on the value of "Young's modulus;" but having ascertained indirectly that, at any rate in the case of some metals, permanent extension will, according to its amount, produce either decrease or increase of elasticity, I was induced to make a set of observations in which torsion was combined with longitudinal traction.

Fig. 4.



Let P Q R S, fig. 4,* represent a portion of the wire in the unstrained condition; and suppose that, the upper end having been fixed, the lower end is twisted in the contrary direction to the hands of a watch, thus causing the portion A B C D to be extended along the diagonal A C and compressed along the diagonal B D; if now a load be applied at the lower end S R, this will cause the wire to twist still further or to untwist, according as the extension produced by the load along A C is greater or less than that along B D.

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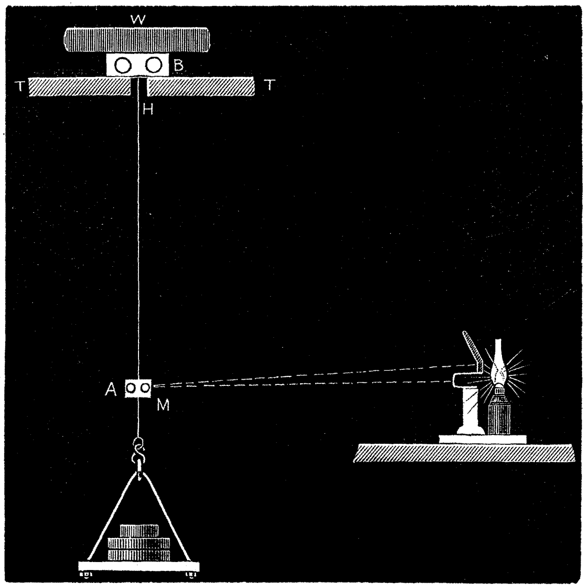
weight permanently on the wire, this weight may exceed that required for the above-mentioned limit. It is quite possible, also, that if the permanent extension and the heavy loading during rest be carried to very great excess, any load however small may exceed the first limit.]

[*] 'Electricity and Magnetism,' Clerk Maxwell, vol. ii., p. 86.

Mode of experimenting.

The wire to be examined passed through a small hole, H, fig. 5, made in a stout table, and was clamped at its upper extremity into a brass block, B, the latter resting on the table and being sufficiently secured by a heavy weight, W, placed on the top of it. Near the lower extremity, which was looped to receive a scale-pan, was clamped a second small block, A, to one end of which was attached a light mirror of the kind employed with reflecting galvanometers; this mirror, used in connexion with a scale and lamp, enabled the observer to detect very small differences of torsion; the distance of the scale from the mirror was 1200 scale-divisions, and the length of each wire at the commencement of each experiment was 95 centims.

Fig. 5.



In the following table will be found the results of the experiments made with the different metals, these latter being for the most part pieces of the same wires as had been used in the determinations of "YOUNG'S modulus," but in each case carefully re-annealed.

TABLE I.—Number of complete turns of permanent torsion produced before the application of the load $=n$. Temporary alteration of torsion produced by the load in terms of divisions of the scale $=\alpha$; $+$ signifies further twist, $-$ untwist on loading.

a.

Iron, diameter=·082 centim.

n.	*k.*	*a.*		
		5 mins. 0	½ hr. 0	16 hrs. 0
10	2	5·0+	5·0+	6·3+
	4	9·0+	11·5+	12·3+
	6	8·5+	13·0+	19·3+
	8	8·0+	14·0+	22·5+
	10	3·0−	14·0+	..
		16 hrs. 0	16 hrs. 12	Average pan 2 kilogs.
50	2	12·5+	12·8+	12·8+
	4	..	20·3+	10·2+
	6	..	29·0+	14·5+
	8	..	37·2+	9·3+
	10	..	44·2+	8·8+
		16 hrs. 0		Average pan 2 kilogs.
130	2	23·0+	..	23·0+
	4	44·5+	..	22·3+
	6	61·0+	..	20·3+
	8	89·5+	..	22·4+
	10	95·0+	..	19·0+
	5 mins. 0			
280	2	20·7+	..	..
	4	29·5+	..	..
	6	32·0+	..	..
	8	36·0+	..	..
	10	36·2+	..	..

b.

Platinum, diameter=·076 centim.

n.	*k.*	*a.*	
		5 mins. 0	Average pan 2 kilogs.
50	2	75·5+	75·5+
	4	160·0+	80·0+
	6	251·5+	83·5+
		36 hrs. 2	Average pan 2 kilogs.
	2	74·0+	74·0+
	4	149·0+	74·5+
	6	237·0+	79·0+
		5 mins. 0	
100	6	322·3+	..
		2 hrs. 6	Average pan 2 kilogs.
	2	103·5+	103·5+
	4	210·5+	105·3+
	6	327·0+	109·0+
		5 mins. 0	
150	6	412·5+	
		5 mins. 0	16 hrs. 0
250	6	477·0+	472·0+
		5 mins. 0	
300	6	514+	..
		5 mins. 0	
348	6	522+	..
	Broke.		

TABLE I. (continued)—Number of complete turns of permanent torsion produced before the application of the load $=n$. Temporary alteration of torsion produced by the load in terms of divisions of the scale $=\alpha$; $+$ signifies further twist, $-$ untwist on loading.

c.

Copper, diameter = ·152 centim.

n.	*k.*	*a.*		
		5 mins. 0		
50	12	·5+		
		5 mins. 0	¼ hr. 12	7 hrs. 12
150	2	..	..	7·5−
	4	..	..	15·5−
	6	..	..	25·5−
	8	..	..	..
	10	..	..	43·5−
	12	42·5−	51·3−	53·5−
		5 mins. 0	1 hr. 12	14 days. 0
250	4	..	41−	49·5−
	8	..	87−	92·2−
	12	135−	139−	143·0−
		5 mins. 0	2 hrs. 12	Average pan 2 kilogs.
450	4	..	103·5−	51·8−
	8	..	200·5−	50·1−
	12	277−	304·0−	50·7−
490	Broke			

d.

Silver, diameter = ·076 centim.

n.	*k.*	*a.*
		16 hrs. 4
20	2	8+
	4	15+
120	2	83−
	4	170−
220	4	297−
320	2	285−
	4	547−
417	2	324−
	Broke	

e.

Aluminium, diameter = ·096 centim.

n.	*k.*	*a.*
		2 hrs. 2
5	2	42+
20	2	142−
120	2	513−

f.

Tin, diameter = ·098 centim.

n.	*k.*	*a.*
		5 mins. 0
5	·05	20−
10	·05	20−
20	·05	32−
40	·05	30−
80	·05	20−

g.

Lead, diameter = ·098 centim.

n.	*k.*	*a.*
		5 mins. 0
5	·05	8+
15	·05	5+
35	·05	6+
80	·05	0
	Broke	

h.

Zinc, diameter = ·098 centim.

n.	*k.*	*a.*
		5 mins. 0
20	2	110+
60	Broke	

TABLE I. (continued)—Number of complete turns of permanent torsion produced before the application of the load $=n$. Temporary alteration of torsion produced by the load in terms of divisions of the scale $=\alpha$; $+$ signifies further twist, $-$ untwist on loading.

k. Hard piano steel, diameter = ·082 centim.		
n.	*k.*	*a.*
		5 mins. 0
5	4	171−
	8	193−
	12	198−
		12 hrs. 12
5	4	162−
	8	192−
	12	192−
Same wire partially annealed		
		2 hrs. 12
10	4	44·5−
	8	52·0−
	12	47·0−
Same wire completely annealed		
		5 mins. 0
15	4	29+
	8	100+
		½ hr. 8
15	4	34+
	8	58+

l. Copper, diameter = ·096 centim.		
n.	*k.*	*a.*
		5 mins. 0
10	6	103+
20	6	153+
40	6	151+
		2 hrs. 9
40	6	112+
		2 hrs. 12
40	6	53+
	10	100+
		½ hr. 13
40	6	50·5+
	10	95·0+
		½ hr. 14
40	6	44·5+
	10	88·0+
Total permanent increase of length produced by the loading = 10 per cent.		

TABLE I. (continued)—Number of complete turns of permanent torsion produced before the application of the load $=n$. Temporary alteration of torsion produced by the load in terms of divisions of the scale $=\alpha$; $+$ signifies further twist, $-$ untwist on loading.

m. Iron, a piece of the same hank as that used in *a*, but heated to a bright red and suddenly cooled.			*n.* Copper, a piece of the same wire as used in *l*.			*o.* Iron, a piece of the same wire as that used in *a*, but elongated 10 per cent.		
n.	*k.*	*a.*	*n.*	*k.*	*a.*	*n.*	*k.*	*a*
		5 mins. 0			5 mins. 0			5 mins. 0
20	10	76+	140	6	103·5+	10	6	12·2+
120	10	160+	240	6	50·0+			
			340	6	38·0−			24 hrs. 10
10 turns of torsion in the other direction.					½ hr. 11	10	6	17·0+
		5 mins. 0	340	6	102·5−			3 days. 0
	2	16+	Heated to redness by passing a burner several times up and down.			30	6	18·0+
	10	62+						
								12 hrs. 0
			wire cool.		5 mins. 0			
						70	6	7·5+
			340	6	50·0−		10	·8+
			390	6	55·5−			
								2 days. 12
						90	8	7·0−
							12	7·0−

Explanation of and remarks on Table I.

The times given in the various columns represent approximately the intervals between the imparting of the permanent torsion and the testing with the loads, whilst the numbers below the times are the number of kilogs. with which the wire was weighted during these intervals; thus $\overset{5\text{ mins.}}{0}$ means that the wire remained unloaded for five minutes after the permanent torsion had been applied, and $\overset{16\text{ hrs.}}{12}$ that the wire was tested 16 hours after the torsion, having in the meantime sustained a load of 12 kilogs. By unloaded we must understand that the scale-pan weighing 2 kilogs. remained on the wire, except in the cases of lead and tin, when a weight of ·05 kilog. was substituted for that of the pan.

We observe that the annealed metals may be divided into two classes; that iron, platinum, lead, and zinc, after suffering permanent torsion, *twist* temporarily[*] on loading, showing that the load produces greater temporary lengthening in the direction in which the torsion had produced extension than it does in the direction of compression. It seems, however, that if the permanent extensions previous to the loading be carried to excess, the wire will begin to *untwist* on loading; thus in *a* we observed that after 260 turns of permanent torsion the twist produced by loading has begun to diminish and in *o* that, when the wire had been considerably stretched before torsion, after 70 turns the twist is changed to untwist. Moreover, the results in *k* on hard and soft steel, combined with those in *o*, clearly show us that whether the distance between the particles be increased by mechanical means or by hardening by the process of heating and suddenly cooling[†] we ultimately arrive at a point where the twist on loading is changed to untwist.

The second class includes the metals, copper, silver, aluminium and tin; these, like the metals of the first class, at first *twist* temporarily on loading, but after a comparatively small amount of permanent torsion has been applied begin to *untwist* and continue to do so, as far as could be ascertained, until the wires will not bear any further twisting without instantly breaking; indeed, the copper in *c* was broken several times, and became so brittle and hard as to snap, like steel that has been heated to a white heat and suddenly cooled, and yet the wire apparently showed no decrease in the amount of untwisting on loading.

It will further be noticed that the average twist or untwist per kilogramme is nearly the same for the different weights employed, but other experiments on metals of the *first class* showed that when the load became excessive the average twist became less and less, and was finally converted into untwist when the load approached the breaking stress; and moreover whereas with smaller loads the *permanent* effect was in the case of both classes to cause *untwist*, with these larger stresses the wire commenced to *twist permanently*: this latter point is most easily proved with lead or tin, as comparatively small weights are required to break the wires made of these metals.

It may, I think, be fairly concluded from these and the previous experiments, that with all metals the longitudinal elasticity is *diminished* by permanent extension *carried to a certain point*; but *beyond this point increased.*

Analogous results have been obtained by THOMSON with respect to the torsional rigidity of metals[‡] and as we shall see latter on, the action of all physical forces is

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[*] It is perhaps as well to observe here that only the variations of torsion produced by *unloading* are recorded in the table.

[†] Sir W. THOMSON has already ('Brit. Encyc.,' Art.: "Elasticity," § 81) proved that hard steel wire *untwists* on loading, after suffering permanent torsion; but we see that if the steel be softened it acts like iron and *twists* on loading.

[‡] Proc. Roy. Soc., vol. xiv., p. 289, and 'Brit. Encyc.,' Art.: "Elasticity," § 78.

apparently affected in a similar manner by stress and strain whether these latter be due to mechanical force, to magnetization, or to change of temperature.

The influence of rest on the wire, whether the metal is left loaded or unloaded, is also very noticeable in the case of iron, and less but sufficiently so with the other metals; thus we see in *a* that in the case of iron after 10 turns of permanent torsion the amount of twist for 8 kilogs. is five minutes after the permanent torsion, 8 divisions, 14 divisions after a rest of half-an-hour, and 22·5 divisions after a rest of 16 hours.

TORSIONAL RIGIDITY.

The torsional rigidity of the wires was determined by the method of vibrations. The vibrators were similar to those employed by Sir W. THOMSON in his experiments on the rigidity and viscosity of metals,* namely, thin cylinders of sheet brass, supported by a thin, flat rectangular bar. The wire to be tested passed perpendicularly through a hole in the middle of the bar, and was there soldered. The other end of the wire was soldered into a stout iron bar, firmly held in a vice attached to a rigid support.

EFFECTS OF PERMANENT TORSION AND ELONGATION ON THE MODULUS OF RIGIDITY.

THOMSON has proved† that the rigidity of a wire is diminished both by permanent longitudinal extension and by permanent twist. As it seemed desirable to ascertain whether rest would restore any of the rigidity thus lost, and also whether the influences of permanent extension and torsion would be greater on vibrations through large arcs than through small ones, a series of experiments was begun of which the following are examples.

Experiment XIV.

An iron wire was considerably stretched, and the times of vibration ascertained to be—

Number of minutes after stretching.‡	Time of vibration.
	Seconds.
5	3·040
25	3·025
35	3·019
45	3·015
1440	3·000
2880	2·996

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* Proc. Roy. Soc., vol. xiv., p. 289.

† 'Brit. Encyc.,' Art.: "Elasticity," §§ 78, 81.

‡ The vibrations were generally counted in each trial for about 10 minutes, and the times are reckoned from the commencement of each trial. The initial arc of vibration was in each case 10°.

Experiment XV.

A copper wire was elongated by 10 per cent., and when vibrated gave the following results :—

Number of minutes after stretching.	Time of vibration.
	Seconds.
1	4·348
11	4·337
120	4·330
1440	4·316

Experiment XVI.

An iron wire about 4½ feet long received 50 turns of permanent twist and was then tested :—

Number of minutes after torsion.	Time of vibration.
	Seconds.
1	3·0415
180	3·0200
1440	3·0000

Experiment XVII.

A copper wire about 4½ feet long received 50 turns of permanent twist and gave the following results :—

Number of minutes after torsion.	Time of vibration.
	Seconds.
1	4·615
2	4·500
5	4·488
1440	4·444

Experiment XVIII.

The time of vibration of a copper wire which had suffered no permanent torsion was, when vibrated through a small arc, 6·242 seconds, and when started with a twist of three revolutions* 6·316 seconds, there being thus a difference of ·074 second. The wire was now subjected to 100 turns of permanent torsion, and in a few minutes

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* Only 19 vibrations were counted in each trial, so that the amplitude of vibration might not be diminished too much.

afterwards vibrated once in 6·431 seconds through small arcs, and in 6·58 seconds when started with a twist of three revolutions. The difference between the two times is now ·149 second or twice the former difference. After a rest of 24 hours the two times became respectively 6·370 and 6·474, and the difference ·104 second.

Experiment XIX.

An iron wire, 4½ feet in length, was vibrated through different arcs for 30 seconds in each of several trials, and the means of these taken as the time of vibration.

Number of degrees in initial arc of vibration.	Mean time of oscillation.
°	Seconds = t.
10	1·200
90	1·250
180	1·244
90	1·228
10	1·200
360	1·210
180	1·188
720	1·250
360	1·245
180	1·220
90	1·182
10	1·200

Previous to these trials the wire had received 10 turns of permanent torsion, which had had the effect of diminishing the rigidity.

Vibrating the wire caused, in this instance, as it does in all cases where the metal has received permanent torsion, a certain amount of untwisting depending upon the amplitude of the arc of vibration.*

Experiment XX.

A piano-steel wire was vibrated several times, for about 30 seconds each time, through 1080°, and the time of vibration was found to diminish on each trial until the fourth, when it became constant. It was then vibrated through smaller and smaller arcs with the following results :—

Initial arc of vibration.	Time of vibration.
°	Seconds = t.
1080†	1·647
720	1·662
360	1·677
10	1·706

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* In consequence of this untwisting the vibrations were, in experiments of this kind, counted from the *beginning of the swing*, and not, as is usual, from the position of equilibrium.

† The elasticity of the wire was perfect for this degree of torsion.

Remarks on the above experiments.

It appears from Experiments XIV.–XVIII. inclusive (1) that the loss of rigidity produced by twisting or stretching a wire beyond the limits of elasticity, is partly diminished by rest; (2) that the loss is more sensible with large arcs of vibration than with small ones; and (3) that the influence of rest is more apparent in the case of large vibrations than in that of small ones.

Experiment XIX. shows that continual vibrating through large arcs has a similar effect on the rigidity to that produced on the longitudinal elasticity by heavily loading and unloading, the time of vibration through large arcs being by the former process made less, just as the temporary elongations caused by heavy loads are diminished by the latter.

Finally, Experiment XX. shows that in the case of a wire possessing great coercive force, the effect of vibrating through a large arc for several minutes actually makes temporarily the rigidity, as determined from such vibrations, *greater* than that determined from smaller vibrations: an effect analogous to that produced by leaving a wire heavily weighted for some time, when, as we have seen, the temporary effect on the length of large loads is less in proportion than of small ones.

We thus see that the effect of permanent torsion on the torsional rigidity is similar in every respect to the effect of longitudinal extension on the value of YOUNG'S modulus."

Iron, aluminium, copper, and silver are the only metals which have, as yet, been tested in the above-mentioned manner, and iron, as before, is conspicuous for the large influence on it of continued rest.

In Table II. will be found embodied the results obtained in the case of each substance for the modulus of rigidity and "YOUNG'S modulus," together with some other data which are further supplemented in Table III.*

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* For observations on the moduli of elasticity of nickel and carbon at the ordinary temperature of the room, and of iron, steel, nickel, and copper at the temperature at 100° C., see Part II.

TABLE II.

Name of metal.	Condition.	Specific gravity of water at 4° C. = 1. Δ.	Torsional rigidity in grms. per square centim. r.	YOUNG'S modulus in grms. per square centim. e.	Ratio of lateral contraction to linear elongation. σ.
Iron (1)*	Annealed	7·759	$773·1 \times 10^6$	1981×10^6	·281
Iron (2)	Hard drawn	7·740	$771·1 \times 10^6$	2041×10^6	·325
Iron (3)	Hard drawn	7·520	$637·2 \times 10^6$	1683×10^6	·321
Piano steel (1)	Hard drawn	7·814	$746·5 \times 10^6$	1894×10^6	·269
Piano steel (2)	Hard drawn	7·784	$782·3 \times 10^6$	1968×10^6	·259
Platinum (1)	Hard drawn	21·323	$686·4 \times 10^6$	1443×10^6	·051
Platinum (1)	Annealed	21·300	$692·7 \times 10^6$	1490×10^6	·076
German-silver (1)	Annealed	8·700	$493·7 \times 10^6$	1335×10^6	·354
German-silver (2)	Annealed	8·632	$456·2 \times 10^6$	1291×10^6	·415
German-silver (2)	Hard drawn	8·632	$389·6 \times 10^6$	1169×10^6	·500
Copper (1)	Annealed	8·913	$440·6 \times 10^6$	1160×10^6	·315
Copper (1)	Hard drawn	8·896	$418·2 \times 10^6$	1449×10^6	·733
Copper (2)	Annealed	8·851	$419·3 \times 10^6$	1218×10^6	·453
Copper (3)	Annealed	8·825	$457·4 \times 10^6$	1143×10^6	·293
Platinum-silver (1)†	Annealed	12·623	$369·9 \times 10^6$	1051×10^6	·420
Platinum-silver (1)	Hard drawn	12·608	$302·3 \times 10^6$	1038×10^6	·717
Brass (1)	Hard drawn	8·396	$321·1 \times 10^6$	$988·4 \times 10^6$	·587
Brass (2)	Hard drawn	8·488	$332·5 \times 10^6$	$988·1 \times 10^6$	·504
Zinc (1)	Hard drawn	7·138	$338·4 \times 10^6$	$766·9 \times 10^6$	·133
Silver (1)	Annealed	10·491	$271·8 \times 10^6$	$742·4 \times 10^6$	·367
Silver (1)	Hard drawn	10·434	$274·6 \times 10^6$	$764·5 \times 10^6$	·392
Aluminium (1)	Hard drawn	2·730	$249·8 \times 10^6$	$669·4 \times 10^6$	·340
Aluminium (1)	Annealed	2·732	$265·2 \times 10^6$	$673·1 \times 10^6$	·269
Tin (1)	Drawn	7·264	$120·9 \times 10^6$	$277·1 \times 10^6$	·145
Lead (1)	Drawn	11·193	$74·0 \times 10^6$	$167·0 \times 10^6$	·136

Remarks on Table II.

The determinations of r were made in all cases with unstretched pieces of the different wires, and may for the most part be considered as extremely accurate, but in the cases of tin and lead it was found very difficult to obtain good observations on account of the great viscosity of these metals; indeed, with the former only *four* vibrations of convenient amplitude could be counted.

Tin, lead, zinc, and aluminium are placed in the order of their viscosity.

The annealed and hard drawn wires having the same numbers attached to them in the tables are not the *same pieces* but are cut from the *same hank*. I should have employed actually the same pieces in the two conditions, had I not wanted them for the purposes mentioned in Part II.

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* This metal and copper (3) I obtained through the kindness of Sir W. THOMSON; their moduli of elasticity had been carefully determined by T. GRAY, in the Physical Laboratory of Glasgow University. Iron (2), (3), steel (1), (2), and brass (2) were tested some years ago by myself with the cathetometer.

† This alloy was composed of two parts by weight of silver and one of platinum.

The values of Δ were determined very carefully, more so perhaps than was necessary. The specimens used for this purpose had not been stretched, and when in the water were well freed of air bubbles by brushing. The results are certainly correct to the third decimal place.

The ratio of lateral lineal contraction to longitudinal dilatation was calculated from the formula $\sigma=\frac{e}{2r}-1$* on the assumption of the wires being isotropic. It seems evident, however, that the values of σ thus obtained cannot claim to be even approximately correct when the metal has been rendered very hard by the process of drawing, as was the case with copper (1), platinum-silver (1), brass (1), brass (2), and German-silver (2) : here we meet with apparently impossible results.

The mean value of σ for the *different* substances† employed in the *annealed* condition $=\cdot2515$, a number closely according with that assigned by POISSON as the value of σ for *each.*

The metals copper (1), copper (2), platinum, aluminium, silver, and platinum-silver were obtained from Messrs. JOHNSON, MATTHEY, and Co. as chemically pure, and the zinc, lead, and tin wires as being as pure as could be got by the ordinary process of distillation.

ELASTICITY OF VOLUME.

If e denote the value of "YOUNG'S modulus," and σ the ratio of lateral contraction to longitudinal extension, it can easily be proved that the elasticity of volume $=\frac{1}{3}\cdot\frac{e}{1-2\sigma}$, and as e in Table II. is measured in grammes per square centimetre, it follows that the increase of volume per unit resulting from a longitudinal stress of 1 grm. per square centimetre $=\frac{1-2\sigma}{e}$.

In the following table are given the values of the volume elasticity, which will be denoted by v, and of the alteration of volume $\frac{1}{3v}$ produced by the above stress.

In the same table, in order to complete the information given in Table II., is recorded the section of each wire in square centimetres; the section of the hard-drawn metals in Table II. being approximately equal to those given here for the annealed wires.

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* THOMSON and TAIT'S Nat. Phil., p. 521.

† Copper (2) is not included in this estimate, as I have reason to believe that it was imperfectly annealed.

TABLE III.

Name of metal.	Elasticity of volume $= v = \frac{e}{3(1-2\sigma)}$.	Alteration of volume produced by longitudinal stress of 1 grm. per square centim. $= \frac{1}{3v}$.	Section in square centims.
Iron	1508×10^{6}	$221 \cdot 1 \times 10^{-12}$	6550×10^{-6}
Platinum (1)	$585 \cdot 7 \times 10^{6}$	$569 \cdot 0 \times 10^{-12}$	5178×10^{-6}
German-silver (1). . . .	1524×10^{6}	$218 \cdot 7 \times 10^{-12}$	5731×10^{-6}
Copper (1)	1045×10^{6}	$319 \cdot 0 \times 10^{-12}$	7310×10^{-6}
Copper (3)	$920 \cdot 3 \times 10^{6}$	$362 \cdot 3 \times 10^{-12}$	18330×10^{-6}
Platinum-silver (1) . . .	2190×10^{6}	$152 \cdot 2 \times 10^{-12}$	7681×10^{-6}
Zinc (1)*.	$348 \cdot 3 \times 10^{6}$	$957 \cdot 0 \times 10^{-12}$	8144×10^{-6}
Silver (1)	$930 \cdot 3 \times 10^{6}$	$358 \cdot 3 \times 10^{-12}$	5464×10^{-6}
Aluminium (1).	$316 \cdot 0 \times 10^{6}$	$1055 \cdot 0 \times 10^{-12}$	8632×10^{-6}
Tin (1)	$130 \cdot 1 \times 10^{6}$	$2562 \cdot 3 \times 10^{-12}$	7758×10^{-6}
Lead (1).	$76 \cdot 5 \times 10^{6}$	$4360 \cdot 0 \times 10^{-12}$	7374×10^{-6}

Remarks on Table III.

There is little to be said with reference to this table except to call attention to the great alteration which takes place in the order of several of the metals, with reference to their elasticity of volume, and that occupied by them in the tables of "YOUNG's modulus." We find, for instance, platinum, which in the latter table stands second on the list of annealed metals, here ranking as seventh, whilst the alloys, platinum-silver and German-silver, are both higher than iron, the former of the two alloys conspicuously so. It would seem, moreover, that either small reliance can be placed on the method of determining the ratio of lateral contraction to linear elongation from observations of the longitudinal elasticity and torsional rigidity, or else that the volume elasticity varies considerably with different specimens of the same metal; for instance, the mean value for the modulus of bulk elasticity in the case of the two specimens of annealed copper recorded in the last table is 982×10^{6}, whereas THOMSON† gives the corresponding value for copper as 1717×10^{6}.

PERMANENT ALTERATION OF DENSITY PRODUCED BY LONGITUDINAL TRACTION.‡

A few experiments were made with a view to determine the *permanent* alteration of density which can be produced by longitudinal traction. Two methods were adopted:

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* Zinc, tin, and lead are, though in the drawn condition, added to this list, as the process of drawing had not hardened them in any degree sufficient to make much difference in either the torsional rigidity or the modulus of elasticity.

† 'Brit. Encyc.,' Art.: "Elasticity," Table I.

‡ For observations on the alteration of density produced by torsion and hammering, see Part II.

in the one the wire was lengthened by successive loads put on for three minutes each and then removed; in the other the wire was stretched by the hand or by the aid of a lever by equal amounts each time until breaking ensued. The balance used in determining the density was an exceedingly good instrument made for me by OERTLING for the purpose of measuring the coefficients of thermal expansion of the metals by weighing them in water at different temperatures. It will suffice here to state that it was possible with this instrument to weigh an object in water to $\frac{1}{10}$th of a milligramme. The air bubbles clinging to the sides of the metals were carefully brushed off, as it was not possible to boil them off, for fear of partially annealing the wires, and the proper corrections were made for temperature and air displaced. The following experiments serve to illustrate the general nature of the results obtained by the two methods:—

Experiment XXI.

SILVER (1).

Load in kilogs. used in producing extension.	Specific gravity water at 4° C. = 1.	Total percentage of increase of length = *dl*.	Total percentage of decrease of specific gravity = *d*Δ.	$\frac{d\Delta}{dl}$.
1	10·47691	. .	. .	. .
6	10·47561	1·15	·0124	·0108
7	10·47207	3·64	·0461	·0127
7·75	10·46754	7·28	·0892	·0123
8·25*	10·46153	9·38	·1465	·0156

Experiment XXII.

COPPER (1).

Load in measures of water, each measure = 2·5 kilogs.	Specific gravity water at 4° C. = 1.	Total percentage of increase of length = *dl*.	Total percentage of decrease of specific gravity = *d*Δ.	$\frac{d\Delta}{dl}$.
5	8·8252	. .	. .	. .
9	8·8251	2·58	·00113	·00044
10	8·8247	4·21	·00566	·00134
11	8·8102	6·94	·1699	·02448
12	8·8076	10·74	·1993	·01856
13	8·7968	16·27	·3216	·01977

* Wire broken.

Experiment XXIII.

IRON.

Specific gravity water at 4° C. = 1.	Total percentage of increase of length = dl.	Total percentage of decrease of specific gravity = $d\Delta$.	$\frac{d\Delta}{dl}$.
7·7849	. .	. .	. .
7·7771	9·35	·1002	·0107
7·7747	12·65	·1311	·0104
7·7730	16·87	·1529	·0091
7·7684	20·73	·2121	·0091
7·7520	25·41*	·4229	·0167

It will be observed that in all cases the ratio of the decrease of specific gravity to the increase of length at first increases to a maximum, then decreases, and again increases largely when the breaking strain has been reached. In any case, however, the alteration of density which can be produced by longitudinal traction is small, and in my own experiments never reached $\frac{1}{2}$ per cent., though several of the wires were strained to breaking.

WERTHEIM has also obtained similar results.†

RELATION BETWEEN MODULI OF ELASTICITY AND INTERMOLECULAR DISTANCE.

If we denote the specific gravity of a substance by Δ, and A represent the atomic weight, the intermolecular distance will be proportional to $\left(\frac{A}{\Delta}\right)^{\frac{1}{3}}=\alpha$.

It is natural to suppose that as α diminishes the elasticity will increase, and in fact WERTHEIM has shown‡ that is the case, and moreover that approximately "YOUNG'S modulus" varies inversely as α^7.

In the next table will be found the products of $e\times\alpha^7$ and $r\times\alpha^7$ for the annealed metals.

TABLE IV.

Metal.	Specific gravity $=\Delta$.	Atomic weight A.	Intermolecular distance $=\left(\frac{A}{\Delta}\right)^{\frac{1}{3}}=\alpha$.	$e\times\alpha^7$.	$r\times\alpha^7$.
Iron (1)	7·759	56·0	1·932	1994×10^8	778×10^8
Platinum (1)	21·300	197·4	2·100	2688×10^8	1250×10^8
Copper (1)	8·913	63·5	1·924	1133×10^8	430×10^8
Zinc (1)	7·138	65·0	2·088	1328×10^8	586×10^8
Silver (1)	10·491	108·0	2·175	1712×10^8	627×10^8
Aluminium (1) . . .	2·732	27·5	2·159	1473×10^8	580×10^8
Tin (1)	7·264	118·0	2·533	1852×10^8	812×10^8
Lead (1)	11·193	207·0	2·644	1510×10^8	669×10^8

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* Wire broke.

† Ann. de Chimie, 1844, tom. xii.

‡ Ibid.

The mean values of $e \times \alpha^7$ and $r \times \alpha^7$ are respectively 1711×10^8 and 717×10^8, and as in WERTHEIM'S results, platinum and copper differ in respect to these products from the mean values, more than the other metals. I have ascertained, however, that there is greater accordance between both $e \times \alpha^7$ and $r \times \alpha^7$, in the case of the different metals, than can be obtained by taking the products of e and r with any other power of α.

THE INFLUENCE OF AN ELECTRIC CURRENT AND OF MAGNETISM ON THE TORSIONAL RIGIDITY OF METALS.

WERTHEIM has shown* that the longitudinal elasticity of metals is temporarily diminished by the passage of an electric current, independently of the alteration which would result from the elevation of temperature produced by the current: he has also proved that *long-continued* magnetization diminishes both temporarily and permanently the elasticity of iron and steel, but that if the magnetization be continued for only a short time there is no sensible effect. As it seemed desirable to supplement these observations by others on the torsional rigidity of metals, a few experiments were made with this object.

Experiment XXIV.

A copper wire, 8 feet in length and ·095 centim. in diameter, was suspended for observations of the torsional rigidity in the manner previously described. To the centre of the flat bar which carried the cylinder was soldered a piece of platinum wire, about 3 inches in length and ·05 centim. in diameter; the other extremity of this latter wire, which hung vertically downwards, dipped into a mercury cup, so that by means of the cup and a silk-covered copper wire soldered to the upper bar, from which was suspended the wire under examination, connexion could be made with a battery of GROVE'S cells, in the circuit of which was placed a GAUGAIN-HELMHOLTZ'S tangent galvanometer; with this galvanometer the current of one DANIELL'S cell freshly charged with sulphuric acid diluted with seven parts of water and sulphate of copper solution, a deflection of 24·9° was produced through a resistance of ·71 ohm.

Observations.	Time of one vibration.	Current.	Total percentage of diminution of rigidity caused by the current.	Percentage decrease of rigidity produced by heating effect of current.	Percentage decrease of rigidity caused by the current proper.
	Seconds.				
Platinum wire out of mercury cup	5·570	0	. .	. .	. .
Platinum in cup	5·568	0	. .	. .	. .
Wire shortened	5·355	0	. .	. .	. .
	5·395	73°·4	1·54	·63	·91
	5·361	0	1·26	·63	·63

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* Ann. de Chimie, 1844, tom. xii., p. 610.

Experiment XXV.

Iron wire about 8 feet in length and ·13 centim. in diameter.

Observations.	Time of vibration.	Current.	Total percentage of diminution of rigidity caused by the current.	Percentage of diminution of rigidity produced by heating effect of current.	Percentage of diminution of rigidity produced by the current proper.
	Seconds.				
	4·153	0°	. .	. .	. .
	4·197	65°·8	2·10	1·30	·80
	4·155	0°	2·00	1·30	·70
	4·207	68°·2	2·48	1·60	·88
After three days' rest . . .	4·180	0°	. .	. .	. .
	4·177	28°·5	·14—	·05	·19—
	4·191	46°	·52	·25	·27
After three days' further rest . .	4·161	0°	. .	. .	. .
	4·252	71°	4·34	2·05	2·19
After three days' further rest . .	4·164	0°	. .	. .	. .
	4·164	16°·3	0	. .	. .

Experiment XXVI.

A piece of the same kind of iron wire as that used in the last experiment, about 35 centims. in length, was placed in the axis of a magnetizing helix, 30 centims. in length; the helix consisted of 1,200 turns of copper wire $\frac{1}{20}$th of an inch in diameter, wound round a glass tube of 3 centims. inner diameter and 3 centims. thickness.

Time of vibration.	Temperature of wire.	Current.	Total percentage of diminution of rigidity caused by the magnetizing current.	Percentage decrease due to heating effect of the current.	Percentage decrease of rigidity due simply to magnetization.
Seconds.	° C.	°			
1·739	10	0	. .	. .	. .
1·743	16	80	·46	·28	·18
1·722	14	0	2·42	·07	2·35

Several other experiments of the same kind as the last were made with different magnetizing helices and current strengths, and all seemed to show that slight temporary diminution of rigidity is produced by high magnetizing force; but that magnetizing forces small in comparison with that indicated in the last table, and yet sufficient to cause very sensible magnetization, produced no sensible effect. The vibrations were counted for at least half an hour in each determination, and an initial arc of 10° of torsion was employed in all cases. The percentage decrease of rigidity produced by the rise of temperature caused by the current was calculated from KOHLRAUSCH'S formulæ,[*] for iron

$$n=n_0(1-\cdot000447t-\cdot00000052t^2),$$

and for copper

$$n=n_0(1-\cdot00052t-\cdot00000028t^2);$$

where n_0 and n represents the rigidity at 0° C. and t° C. respectively. In Experiment XXVI. a delicate thermometer was placed near the wire, half-way down the helix, and the rise of temperature calculated from the mean of several readings taken from time to time during the passage of the current. In Experiments XXIV. and XXV. the rise of temperature was determined in the following manner:—A current of 70° was passed through the copper wire used in Experiment XXIV., and the soldered junction of a thermo-element, made of fine German-silver and iron wires, each about 2 feet in length, was kept in close contact with the copper wire by placing the latter between the two former; the other ends of the wires forming the thermo-element were connected by means of silk-covered copper wire with the terminals of a galvanometer, and after being wrapped in tissue paper and cotton-wool, were placed in a clip-stand, which was drawn on one side so as to slightly press the soldered junction against the suspended copper wire, a layer of tissue paper having been used to insulate the latter from the former. After a short time the deflection of the galvanometer became constant, and on immersing the junction of the thermo-element in water, it was found necessary to raise the temperature 8·5° C. in order to produce the same deflection as before; 8·5° C. was therefore assumed to be the rise of temperature which would be caused in the copper wire by the above-mentioned current, and the rise of temperature produced by the other currents was calculated from the assumption that the heat generated would be proportional to the square of the current strength. In the case of the iron wire it was assumed that the specific resistance of the iron would be six times that of the copper, and the rise of temperature was calculated accordingly.

An examination of these last tables shows apparently that the torsional rigidity of copper and iron is temporarily decreased by the passage of a powerful current, but is very little altered by currents of moderate intensity.[†]

Experiment XXIV. also shows that the dipping of the platinum wire into the mercury-cup did not appreciably affect the time of vibration.

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[*] 'Brit. Encyc.,' Art.: "Elasticity," § 79.

[†] I cannot place so much confidence as I could wish in the results of these particular experiments, as far as the decrease of rigidity by powerful currents is concerned, the method employed for estimating the elevation of temperature produced by the current being evidently only calculated to give a very rough approximation to the true values. I hope, however, to be in a position at some future time to attack the question in an entirely different way.

CRITICAL POINTS.

Several determinations of the *permanent* increase of length produced by loading were made, and led to the discovery that in all *well and carefully* annealed metals there are at least two points at which a sudden change takes place in the ratio of the load to the permanent extension produced thereby; these points have been called critical points, and it appears that changes more or less profound take place in most if not all of the physical properties of the substance when these points are attained.

As, however, the subject will be fully discussed in Part II., where it will be shown how these points can be indirectly determined more accurately than in the ordinary manner, it will suffice here to say that the existence of the first of these critical points seems to prove beyond a doubt that there is *a true limit of elasticity* for each substance, and that this is intimately connected with the value of "YOUNG's modulus."

It would also appear* that at these two critical points sudden changes take place in the density of the substance.

SUMMARY OF PART I.

1. The magnitude of the temporary elongation which can be produced by any load on a wire which has experienced permanent extension is reduced by simply allowing the wire to rest either loaded or unloaded for some time after the permanent extension has taken place.

2. The length of the period of rest necessary to produce the maximum of the effect mentioned in 1 varies considerably with the nature of the metal of which the wire is made; with some metals a few minutes suffice, whilst with others, such as iron or steel, many hours are required.

3. The effect of rest mentioned in 1 is greater in proportion for large loads than for small ones, and apparently vanishes in the case of such small temporary alterations of length as are produced by causing the wire to vibrate longitudinally.

4. The magnitude of the temporary elongation which can be produced by any load on a wire which has suffered recent permanent extension is also reduced by heavily loading and unloading the wire, the rate of reduction diminishing with each loading and unloading.

5. A departure, as far as temporary elongation is concerned, from "HOOKE's law," more or less decided, always ensues after recent permanent extension, even when the weights employed to produce the temporary elongation do not exceed one-tenth of the breaking-load of the wire.

6. This departure is diminished very noticeably in the case of iron, and to a greater or less extent with all metals by allowing the wire to rest for some time either loaded or unloaded; it is also diminished by repeated loading and unloading.

7. With aluminium and zinc, and probably with the more viscous metals tin and

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* See Experiments XXI.-XXIII. inclusive.

lead, both the maximum temporary increase of length which can be produced by any load, and the complete recovery after the removal of the load, are only attained after an interval of several hours, provided that the weights used for the load be not very small compared with the breaking-load.

8. There is a small but decided departure from "HOOKE's law," as far as temporary elongation is concerned, in all cases where the load employed to produce the elongation is of moderate amount; this is the case even when sufficient rest has been allowed to enable the wire to attain its maximum elasticity.

9. We can therefore only obtain by the method of longitudinal vibrations values for "YOUNG's modulus," which are strictly comparable with those got by the method of static extension, by experimenting when we use the latter method with very small loads, and with the wire under the same conditions of stress and strain as those occurring when the former method is adopted.

10. In the case of all metals, permanent extension, if not carried beyond a certain limit, causes, whether rest is or is not allowed after the permanent extension has taken place, a diminution in the value of "YOUNG's modulus," as determined by the method of static extension.

11. If the permanent extension be carried beyond the above-mentioned limit, further permanent increase of length increases the value of "YOUNG's modulus."

12. The limit of permanent extension mentioned in 10 varies considerably with different metals, and with the time which is allowed to elapse after the permanent extension has taken place.

13. In the cases of iron, heavy loading for some time so increases the value of "YOUNG's modulus," as determined by the method of static extension, that even when the extension would have caused, without such loading, diminution of the modulus, this diminution can be changed to an increase; with copper this is not the case.

14. With iron wire which has been heavily loaded for some time, the ratio of the temporary elongation to the load producing it becomes less as the load employed becomes greater, until a certain limit, depending upon the extent of the previous heavy loading, has been reached; whereas with most other metals, and with iron which has suffered permanent extension without allowing the load which has produced the extension to remain for some hours on the wire, the elongation increases at first in greater proportion than the load.

15. The effects on the longitudinal elasticity, and on the torsional rigidity of steel, of suddenly chilling the metal after it has been raised above a bright red heat, are similar to those produced by excessive permanent traction.

16. The loss of torsional rigidity, which is caused by twisting or stretching a wire beyond the limits of elasticity, is diminished by rest.

17. The influence of rest mentioned in 16 is greater in proportion for large arcs of vibration than for small ones, and is more noticeable with iron and steel than with most of the other metals.

18. The loss of torsional rigidity mentioned in 16 is more sensible proportionally with large arcs of vibration than with small ones.

19. Continual vibrating through large arcs has a similar effect on the torsional rigidity to that produced on "YOUNG's modulus" by heavy loading and unloading.

20. The density of a wire is very little altered by permanent extension, even if the latter be carried to the extent of breaking the wire.

21. The values of "YOUNG's modulus" obtained for the different metals are, roughly speaking, inversely proportional to the seventh powers of the mean distances between adjacent molecules in these metals.

22. The torsional rigidity of copper and iron wires seems to be temporarily decreased by the passage of a powerful electric current through the wires.

23. The torsional rigidity of iron wire seems to be temporarily diminished when the wire is subjected to a powerful longitudinal magnetizing force.

24. The effects mentioned in 22 and 23 are apparently independent of any change produced by the electric current or the magnetizing force of the temperature of the wires.

25. There are, in every well-annealed wire, two critical points at which sudden changes take place in the ratio of the permanent extension produced by longitudinal stress which is gradually increased in amount and the magnitude of the stress.

Received January 18,—Read January 26, 1882.

PART II.—ELECTRICAL CONDUCTIVITY.

THE TEMPORARY ALTERATION OF ELECTRICAL CONDUCTIVITY PRODUCED BY LONGITUDINAL TRACTION.

W. THOMSON, in 1856,* investigated the effects of tension on electrical conductivity in copper and iron wires, and, moreover, stated that he "had very nearly established, for the case of iron at least, that the augmented resistance due to tension, either temporary or permanent, is a very little more than can be accounted for by the change of form."

In 1877† I determined in absolute units the amount of alteration produced by longitudinal traction in the resistance of steel, iron, and brass, and proved that the temporary alteration of resistance resulting from increase of length and diminution of section is with iron and steel about two-fifths and with brass four-fifths of the whole observed change.

In the above-mentioned experiments I experienced considerable difficulty in obtaining accurate results in consequence of the minuteness of the changes to be measured, and, therefore, set about devising some plan whereby the variations of resistance caused by slight changes of temperature, which had proved a source of great annoyance, might be eliminated. In this attempt I have been entirely successful, and with the arrangements described below have determined, with I believe considerable accuracy, the very small changes of resistance which can be temporarily produced by mechanical tension.

Description of apparatus.

Pieces, about 7½ feet in length, of the same wires as used in Part I. were suspended in pairs, as in fig. 6‡, in an air chamber 4 feet in height, 4 inches inner diameter and 6 inches outer diameter; the inner of the two concentric cylinders of which the air chamber was composed being surrounded by a layer of water 1 inch thick enclosed between the two cylinders. This vessel, which was made of tinned iron, rested on a table, provided with a suitable aperture, R, and was furnished with two thermometers, T T, passing through the outer cylinder and into the axis of the inner one. The ends of the two wires were clamped into three short and stout brass blocks, A, B, C, which

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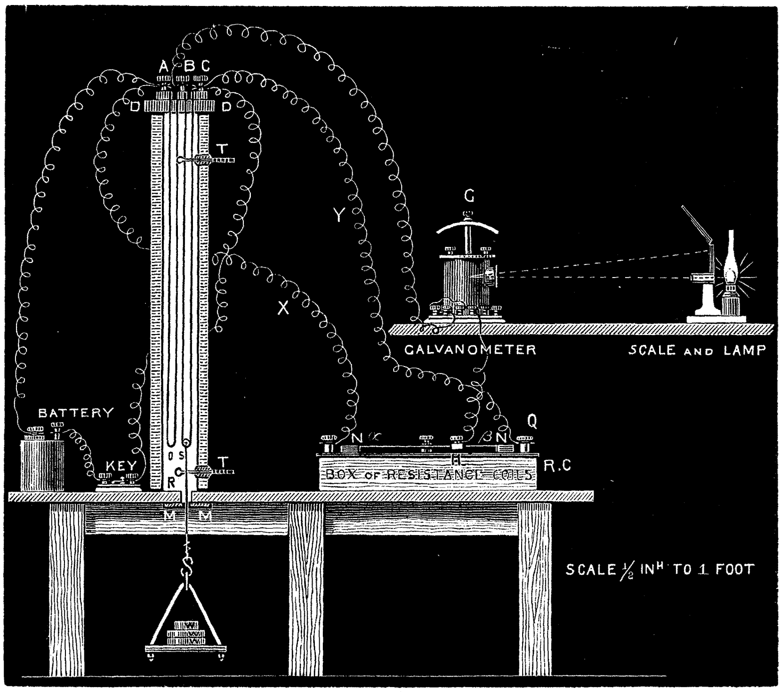
* Phil. Trans., Part IV., Feb. 28th, 1856, §§ 150–152.

† Proc. Roy. Soc., No. 183, 1877.

‡ In this figure the key employed to close the battery circuit is placed near the LECLANCHÉ cell and not in its actual position near the scale and lamp, in order to show the connexions more clearly.

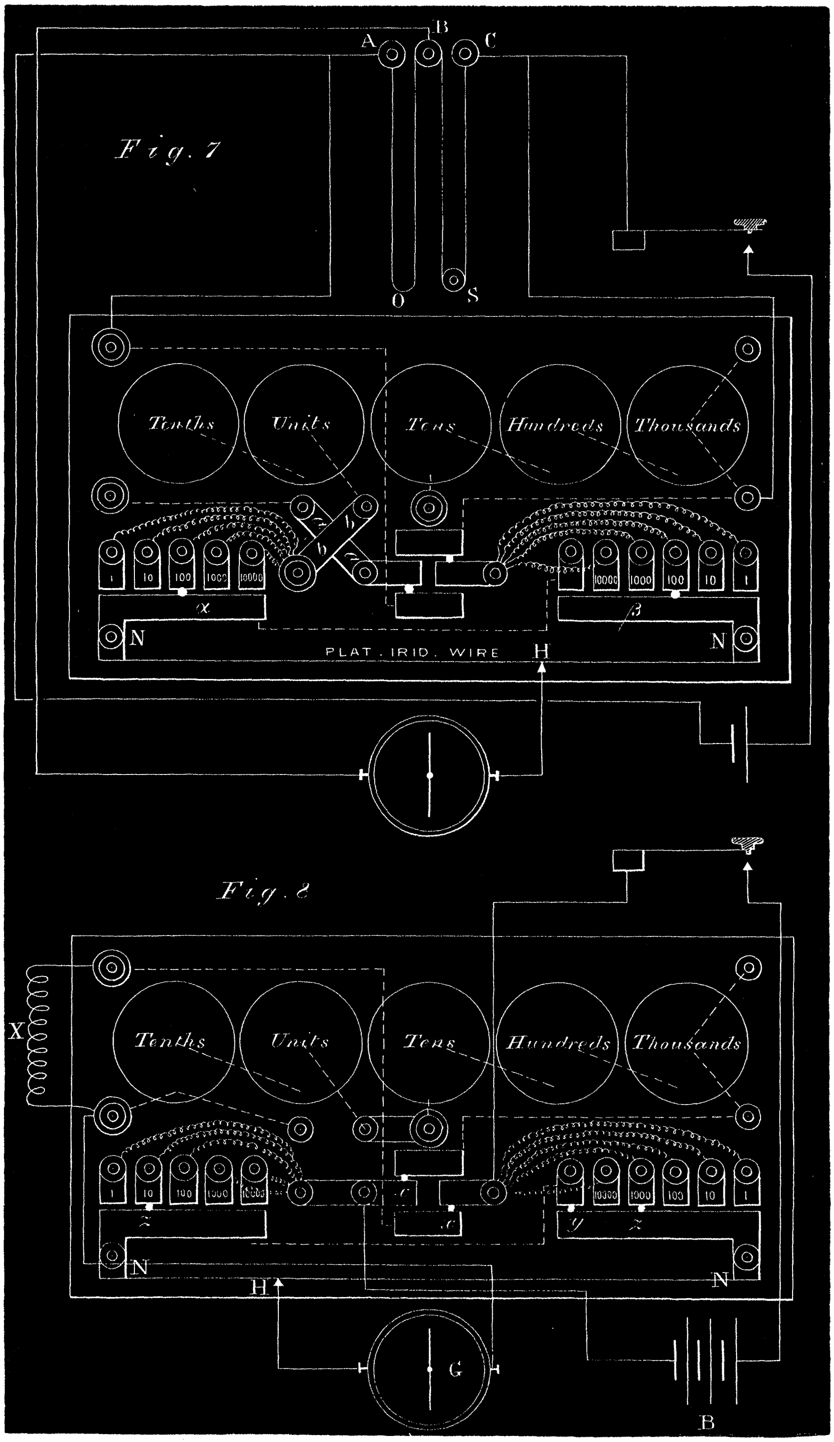
rested upon a support of hard wood, D D, each block being separated from its neighbours by wooden partitions. The block B was double the length of A and C, and into this was clamped one end of each of the wires, the other ends being clamped into A and C. A caoutchouc-covered copper wire connected a binding-screw on A with one

Fig. 6.



pole of a large-sized LECLANCHÉ and a similar wire, X, connected the same binding-screw with a set of resistance-coils (α, fig. 7). In a similar manner C was connected with the other pole of the LECLANCHÉ, and through Y with another set of resistance-coils, β; whilst B, and the sliding-piece H, which traversed a wire, N N, made in the first instance of platinum-silver and afterwards of platino-iridium, uniting α and β, were joined to two terminals of a reflecting galvanometer, G. The wire to be strained was provided with a movable pulley, S, 2 inches in diameter, to which was attached by means of a stout wire the scale-pan used in Part I., or, as in some experiments, a large pail weighing 4 kilogs. and capable of containing about 60 kilogs. of water; both wires were, before suspension, surrounded with caoutchouc-tubing silk or other insulating material. The aperture, R, could be closed by two wooden shutters, M M, having small semicircular holes cut in the centre of the extremities adjacent to each other, so as to leave only just sufficient room for the stout wire to swing freely; moreover, still further to prevent any errors which might be caused by chance currents of air, the top of the air-chamber was well covered with baize after the wires had been adjusted, and the table was also surrounded on three sides with a like material.

Figs. 7 and 8.


A
B
C
Fig. 7
O
S
Tenths
Units
Tens
Hundreds
Thousands
1
10
100
1000
10000
a
b
α
β
N
PLAT. IRID. WIRE
H
Fig. 8
X
x
y
z
G
B

It will be seen that the whole arrangement of wires, battery and galvanometer, forms, with the resistance coils α and β, a "WHEATSTONE's balance," such that no part of the wires to be compared, namely, S and O, is out of the air-chamber. The galvanometer was provided with two sets of needles, which were astatic; the coil surrounding the upper set having a resistance of 7·487 ohms, and that surrounding the lower set a resistance of 4863 ohms, at the temperature 21° C. The wire of the former coil was divided into two equal parts, the ends of these being soldered to four terminal screws, so that, by connecting the two parts of the coil in "Multiple arc," the resistance could, if necessary, be diminished to 1·872 ohms, and the instrument rendered available for experiments requiring a galvanometer of low resistance. The upper coil only was used in this part of the enquiry, and yet the instrument proved so sensitive that, with the single cell employed for the current-motor, and with the adjusting magnet *assisting* the earth's directive force on the needles, a variation of conductivity of 1 part in 100,000* could be readily detected even in the most unfavourable case, which was that of a copper wire having a resistance of only ·0224 ohm; whilst in the majority of instances resistances were *measured within five parts in one million.*

The resistance coils were of platinum-silver, and the wire N N uniting α and β was, in the first few experiments, made of the same material, but was afterwards replaced by one of platinum-iridium; this latter wire was made expressly for me by Messrs. JOHNSON and MATTHEY, and seemed a marvel of accurate wire-drawing, as on testing it at various parts no variation of conductivity could be detected anywhere except at the two extreme ends, where it was firmly clamped into brass blocks; all the graduated portion of the wire, 470 millims. in length, seemed, within the limits of observation, to be perfectly uniform.

When required for measuring resistances in the ordinary way, the coils were arranged as in fig. 8; where X represents the wire under examination, G the galvanometer, B the battery, H the sliding-piece, and x, y, z conical plugs of brass with ebonite heads. Immediately to the right of X are a set of resistance-coils of the "dial pattern," ranging from $\frac{1}{10}$th of an ohm to 10,000 ohms; whilst below these are two sets of resistances, the arrangement and magnitude of which are sufficiently shown in the diagram; the plugs x, x serve to commute the position of X in the bridge, and the plug y to throw out, if necessary, the resistance N N, the dotted lines representing wires of extremely small resistance.

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[*] These beautiful instruments might, if necessary, be rendered even much more sensitive than they are by adopting a finer suspension. I have found that *a single fibre of unspun silk* is quite sufficient to sustain a weight equal to that on the suspension of many of the galvanometers which are now made, and anyone who will take the trouble to test practically, as I have done, the alteration which can be effected in the instrument by the *careful* selection of such a fibre will be surprised at the result. I feel little hesitation in asserting that my own galvanometer could be rendered *three* times as sensitive as it is now by such means; as it is, the silk suspension has been slowly untwisting for upwards of *seven years*, and still continues to do so. I have also found that keeping the galvanometer perfectly stationary, after it has once been placed in position, materially assists in preserving the magnetism of the needles.

For the purpose of this particular part of the enquiry, arrangements were made as in fig. 7, where it will be seen that the crossed pieces *a a*, *b b*, which are insulated from each other, serve to connect the tenths and units with the resistance-coils α.

Examination of the resistance-coils and of the platinum-iridium wire.

In order to test the uniformity of the platinum-iridium wire N N, two platinum-silver wires, of resistances 9 and 10 ohms respectively, were placed in the positions of O and S, fig. 7.

β was supplemented by a rheochord, and at both α and β the plugs were inserted in the 10 ohms resistance, whilst the rheochord was employed to bring H to the extreme right-hand end of the graduated portion of the wire. If, then, r denote the resistance of the ungraduated portion of N N on the right of H, together with the interposed portion of the rheochord and Y, whilst l denotes the resistance of the ungraduated part of N N on the left of H together with X, we have

$$\frac{10+l+(470-n_1)x}{10+r+n_1.x}=\frac{\text{resistance of O}}{\text{resistance of S}}=k \text{ say,}$$

or

$$10+l+(470-n_1)x=k(10+r+n_1.x) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where x is the average resistance of one division of N N, and n_1 is the number of divisions from the right-hand end of the graduated wire at which H is placed.

A resistance of $\frac{1}{10}$th ohm is now added to α from the tenths' dial-plate, and in consequence H has to be moved to n_2 divisions from the right-hand end in order to restore the balance;

$$\therefore\ 10{\cdot}1+l+(470-n_2)x=k(10+r+n_2.x) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

from (1) and (2) we obtain

$$x=\frac{\cdot 1}{(k+1)(n_2-n_1)}.$$

Again the rheochord is adjusted so as to bring H about 10 millims. still further away from the right to, say, n_4 divisions, and on the removal of the $\frac{1}{10}$th ohm resistance H is brought back towards the right to, say, n_3 divisions; then as before

$$x=\frac{\cdot 1}{(k+1)(n_4-n_3)}.$$

If the wire is uniform the value of x in the latter case should be equal to that of x in the former, and therefore

$$n_4-n_3=n_2-n_1$$

This was found to be so exactly the case that though H was provided with a vernier reading to $\frac{1}{10}$th of a millimetre, and the addition of the $\frac{1}{10}$th ohm required H to be shifted through about 300 millims., no difference whatever could be detected between $n_4 - n_3$ and $n_2 - n_1$, the galvanometer being sufficiently delicate to show an alteration of resistance equal to that of $\frac{1}{10}$th of a millimetre of N N. In the same manner each portion of the wire was tested, and it was concluded that no difference of resistance amounting to 1 in 3000 existed in any part of the graduated wire.

The uniformity of N N having been established, it was easy to compare the tenths with each other, and by determining the exact value of k, to find the values of their resistances in terms of the divisions of the platinum-iridium wire: this was accordingly done, and the values thus obtained were ascertained to accord fairly well with each other.

In order to secure still greater accuracy, the wire N N and the whole of the resistance-coils were afterwards tested by means of a second box of resistance-coils,* some eight or nine entire days having been spent in this work. These fresh trials confirmed the results obtained in the previous ones as regards the uniformity of N N and the *relative* values of the tenths; but the *absolute* values of the latter in terms of the divisions of N N were found to vary slightly on different days, as also did those of the rest of the resistance-coils. Thus the sum of the ten resistances in the units dial-plate were found on three separate days to be equal to that of 58,605, 58,739, and 58,437 divisions of N N respectively.†

From these and other experiments the average value of the resistances of each of the units at 17° C, at which temperature a unit agreed, according to KIESER, with 1 ohm, was equal to the resistance of 5859·4 millim. divisions of the platinum-iridium wire.

The units accorded very well with each other and with all the other resistances in the box except the tenths, nearly all the latter being slightly too low. The exact values, however, of each of the units and tenths were tabulated and used in calculating the results of the different experiments made in this and subsequent parts of the enquiry.

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* This box was kindly lent to me by Mr. KIESER, of ELLIOTT Bros., to whom I am also indebted for diagrams 7 and 8.

† These variations are certainly not due to errors of observation, as the results of trials made within one or two hours of each other agreed much more closely with each other; they may be attributed almost entirely to the prevalent plan of embedding resistance-coils in solid paraffin, whereby the temperature of the coils inside the box is frequently very different from that of the air outside: this plan is, I am convinced, a very bad one when great accuracy is required, as not only do the wires get heated to an extent which is very appreciable, even when only a single cell is employed, but a "PELTIER effect" is produced at the junctions of the coils and the brass-blocks which can never be properly got rid of; and thus the labour and care bestowed on these resistances are to a great extent lost. It would be better to fill the box with some such liquid as paraffin oil.

Preliminary trials and final method of experimenting.

In the first attempts which were made the galvanometer was put into circuit by means of the usual contact-piece of the sliding-block H, immediately after closing the battery; but it was soon found that the very act of pressing down the contact-piece generated small thermo-electric currents* which, lasting some minutes, frustrated all attempts at making such accurate measurements as it was hoped would ultimately be obtained. H was therefore clamped by means of a suitable spring-and-catch, with which it was provided, to any desired part of the platinum-iridium wire, and a double key was employed by means of which first the battery and then immediately afterwards the galvanometer were put into the "bridge." Here again, however, exactly the same difficulty was encountered, and by no device of covering the hand and key with cloth or silk could this source of error be entirely avoided. The double key was therefore discarded, and the galvanometer being always kept in the "bridge," a single key was used for closing the battery circuit for the brief space of time necessary for observing whether this act caused any difference of potential at the terminals of the galvanometer.

Of course the zero-point of the galvanometer needles was continually being altered by the thermo-electric currents produced by the frequent shifting and clamping of H, but this circumstance did not affect the results, and though in the case of iron a slight trouble was experienced sometimes from the "kick" of the needles due to circular magnetization, this difficulty was after a few trials surmounted, and from this point the measurements proceeded very satisfactorily.

In most instances α and β were made of about 100 ohms' resistance, and though such large resistances were, it is true, out of proportion to those of the other branches of the bridge, yet, as has been already observed, the arrangement proved of amply sufficient delicacy, and moreover rendered it impossible that any slight variations of the resistances of X and Y, which were each ·042 ohm, and of the wire N N, arising from changes of temperature, should cause any appreciable error; indeed, one great advantage of this method is that the galvanometer and the resistance-coils may be a hundred yards or more from the rest of the "bridge" without any chance of fluctuations of temperature materially influencing the result, even when the most minute variations of electrical conductivity are to be measured.

The deflections of the galvanometer were read in the usual manner by means of the image of a fine wire fixed vertically across one end of a small blackened tube, into the other end of which was fitted a lens for focussing the image of the wire on to the mirror of the galvanometer; and the end of the tube at which the wire was situated was illuminated by a paraffin lamp, placed so that the edge of the flame was in front of the wire, the reflected circle of light with the fine dark line across the centre being very

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* This fact has, I find, been also noticed by GLAZEBROOK, Phil. Mag., April, 1881, No. 68.

clearly defined on the scale, though the latter was at a distance of 6 feet from the galvanometer.*

The adjusting magnet was almost always used to *assist* the directive force of the earth's magnetism on the needles, as it was found that by so doing the shifting of the zero-point caused by the above-mentioned thermo-electric currents was considerably diminished, and at the same time the instrument was sufficiently sensitive. The wires S and O, which were made as nearly as possible of the same resistance, were, after being suspended, allowed to remain in the air-chamber for some time; β was then made 100 ohms and α adjusted, first by the resistances in the box as far as $\frac{1}{10}$th of an ohm, and finally by using the sliding-block H until no deflection of the image of the fine wire could be detected on closing the battery circuit.

As the needles of the galvanometer soon came to rest, and H could be very readily clamped and unclamped, it was possible to make the observations quickly; an interval of one minute was, however, generally allowed to elapse between two consecutive readings, as, though the battery-power was small and S and O of the same material and of the same section, yet in some cases the current evidently produced unequal heating effects in the two wires. Nor is this to be wondered at, as a difference of temperature of less than $\frac{1}{1000}$° C. would produce a sensible difference of resistance.

In ascertaining the temporary alteration of resistance caused by longitudinal traction, it was deemed advisable to adopt the same precautions as were used in determining the modulus of elasticity, as though the wires employed had been previously strained for the latter purpose and then allowed to rest for some weeks; they seemed, in some cases at least, to have become partially annealed, and it was found that the temporary alteration of electrical conductivity caused by loading was affected in precisely the same manner as the elasticity, by stress producing recent permanent extension.

Great care was taken in loading and unloading the wire S, and in the experiments which were made with the first two or three wires a large but light pail was used instead of the scale-pan. Into this vessel measured amounts of water were allowed to flow slowly through a piece of caoutchouc tubing, when it was necessary to apply stress, and the unloading was accomplished by suffering the same water to pass gently out through another piece of tubing connected with an orifice at the bottom of the pail. During the loading this latter tube was hitched up by the side of the vessel. It was found, however, that with practice quite as accurate results could be obtained by using a scale-pan in the ordinary manner, and as time was thereby saved this method was finally adopted.

Formulæ employed.

The temporary alteration of resistance which was in any case produced was so small that it could be measured by the wire joining α to β. If, therefore, A and B denote

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* The distance of the lamp and scale from the galvanometer is not drawn to the same scale in fig. 6 as for the other arrangements, for the purpose of avoiding the taking up of too much space.

the number of millimetre divisions of this wire which have a resistance equal to the branches α and β respectively, including in these the connecting wires X and Y and the parts of the divided wire on either side of H, n be the number of divisions through which it is necessary to move H in order to restore the balance of resistance when disturbed by a load W, and S be the section of the wire, then, denoting by x the increase per unit of resistance which would be produced by a unit load acting on unit area, we have within a sufficiently close degree of approximation

$$x=\frac{(\mathrm{A}+\mathrm{B})\times n\times s}{\mathrm{A}\times\mathrm{B}\times\mathrm{W}}.$$

Again, if x be multiplied by e we obtain the alteration of resistance per unit which would result from doubling the length of the wire by the application of longitudinal traction ; therefore denoting this latter value by y, we have

$$y=e\times x.$$

Part of y is due to mere increase of length and diminution of section; this part $=1+2\sigma$ very nearly. Thus the alteration of the specific resistance produced by the traction

$$=y-(1+2\sigma).$$

It will be seen that x and y are calculated on the assumptions that the change of resistance is directly proportional to the stress and also to the elongation ; both these assumptions were found to be nearly correct, but neither are strictly so.

The following experiment out of many will serve to show (a) that the temporary alteration of resistance is nearly but not quite proportional to the load, and (b) that it is possible to measure with considerable accuracy minute changes of electrical conductivity even when the resistance of the wire used is small.

Experiment I.

An annealed copper wire ·154 centim. in diameter and having a resistance of only ·0224 ohm was loaded by pouring 12 measures of water, each having a weight of 5825 grms., into a pail attached to the pulley on the wire. This load, which was four-fifths of the "breaking-weight," was suffered to remain on the wire for some hours and was then removed. The following consecutive observations were begun next day and extended over three days, two trials being made on each.

The numbers in the column headed "Temporary alteration of resistance" are the divisions of the platinum-silver wire N N, through which it was necessary to shift H in order to balance the effect of the load.

Number of trial.	Number of measures employed for the load.	Temporary alteration of resistance.
I.	3	188·0
	6	383·0
	9	584·0
II.	3	189·0
	6	381·0
	9	581·0
III.	3	188·0
	6	384·5
	9	583·0
IV.	3	189·5
	6	384·0
	9	583·5
V.	3	188·0
	6	385·0
	9	583·0
VI.	3	190·0
	6	384·0
	9	584·0

The mean values for three, six, and nine measures are respectively 188·8, 383·6, and 583·1, and none of the observations differ from these mean values by ·7 per cent.

Thus for the first three measures we obtain a mean alteration of 188·8, for the second 194·8, and for the third 199·5.

Experiment II.

The same wire as in the last experiment, after having been repeatedly loaded with 13 measures, was tested with the same weights as before with the following results:—

Load in measures.	Temporary alteration of resistance.	Average alteration per measure.	Difference between consecutive averages.
3	207·0	69·00	. .
6	416·7	69·45	·45
9	629·4	69·93	·48

Experiment III.

A piece of platinum (1) annealed, which had been repeatedly loaded with 12 kilogs.

Number of kilogs. in load.	Temporary alteration of resistance.	Average alteration per kilog.	Difference between consecutive averages.
4	108·5	27·13	. .
6	163·5	27·25	·12
8	219·0	27·38	·13
10	277·0	27·70	·32
12	339·0	28·25	·55

Experiment IV.

The same wire as in the last experiment, which had been further loaded and unloaded with 15 kilogs. until the recovery had become perfect for this load.

Number of kilogs. in load.	Temporary alteration of resistance.	Average alteration per kilog.	Difference between consecutive averages.
1	27·5	27·50	. .
3	83·0	27·67	·17
5	139·0	27·80	·13
7	195·5	27·93	·13
9	252·5	28·06	·13
11	310·0	28·18	·12
13	368·0	28·31	·13
15	430·0	28·67	·36

Experiment V.

A piece of silver (1) annealed, which had been previously loaded and unloaded with 8 kilogs. until the recovery had become perfect.

Number of kilogs. in load.	Temporary alteration of resistance.	Average alteration per kilog.	Difference between consecutive averages.
2	94	47·00	. .
4	189	47·25	·25
6	285	47·50	·25
8	383	47·88	·38

Experiment VI.

A piece of platinum-silver (1) rendered very hard by drawing, and which had been loaded and unloaded several times with 20 kilogs.

Number of kilogs. in load.	Temporary alteration of resistance.	Average alteration per kilog.	Difference between consecutive averages.
4	79·00	19·75	. .
8	161·80	20·23	·48
12	246·25	20·52	·29
16	330·00	20·63	·11

Experiment VII.

An annealed iron wire which had been loaded for 24 hours with 30 kilogs.

Number of kilogs. in load.	Temporary alteration of resistance.	Average alteration per 2 kilogs.	Difference between consecutive averages.
2	9·0	9·00	. .
4	20·5	10·25	1·25
6	32·2	10·73	·48
8	44·0	11·00	·27
10	56·3	11·26	·26
12	68·5	11·42	·16
14	80·8	11·54	·12
16	92·9	11·61	·07
18	105·1	11·68	·07
20	117·4	11·74	·06
22	129·8	11·80	·06
24	142·3	11·858	·058
26	155·0	11·92	·062

Remarks on Experiments I.–VII. inclusive.

All these experiments prove that the ratio of the resistance-increase to the load is not quite constant; but that the former increases in a greater proportion than the latter. This want of proportionality is seen from Experiments I.–IV. inclusive to be materially diminished, though never entirely made to vanish, by repeated heavy loading and unloading, and it appears impossible to find any single formula which will express exactly the relation between the load and the alteration of resistance for all conditions of the wire; consequently the values of x given in Table I. are calculated from observations made with two weights, the larger never exceeding one-fourth of the "breaking-weight," and being twice the smaller; and the mean of the two numbers obtained by dividing the observed alteration by the load is taken to represent the change produced by unit load, this mean being in no case different from either of the numbers by more than 1 per cent.

The columns in which are recorded the differences between the consecutive average alteration per kilogramme show that when the load employed in determining the temporary alteration of resistance approaches closely to the highest load which has been used in the preliminary operations, a comparatively rapid increase takes place in the ratio of the temporary alteration of resistance to the load.

From Experiments VI. and VII. we learn that in the case of a metal which has been rendered very hard by the process of drawing, or in the case of iron* which has been subjected to a heavy load for some time, the average alteration of resistance per

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* Probably also in the case of any metal possessing a coercive force comparable with that of iron.

unit load increases less and less rapidly up to a certain degree of stress, and afterwards begins to increase more and more rapidly, whereas with the annealed metals the average alteration increases at first by almost equal amounts.

Experiment VIII.

A piece of platinum (1) annealed was loaded and unloaded several times with 12 kilogs., and was immediately afterwards tested, with the following results:—

No. of kilogs. in load.	Temporary alteration of resistance.	Average alteration per kilog.	Difference between consecutive averages.
2	66·5	66·5	. .
4	134·0	67·0	·5
8	276·0	69·0	2·0
After a rest of 20 hours with all stress removed except that of scale-pan.			
2	67·0	67·0	. .
4	136·0	68·0	1·0
8	281·0	70·25	2·25

From the last experiment it is evident that part of the increase of elasticity which is gained by repeated heavy loading and unloading is lost by allowing the wire to rest, and, moreover, that the departure from "HOOKE's law" which we have seen to be appreciably lessened under the influence of the former cause is increased again by the latter.

In Table I. will be found the values of the specific resistance of the different metals, the increase of resistance per unit which is temporarily produced by a stress of 1 grm. per square centimetre, the increase of resistance per unit which would be caused by stress sufficing to double the length of the wire, and the increase of specific resistance per unit which would be caused by stress sufficing to double the length of the wire; the specific gravity and section of the wire are approximately the same as those recorded in Part I.

TABLE I.

Name of metal.	Condition.	Specific resistance at 12° C., *i.e.*, resistance in ohms of 1 cubic centim., between opposing faces $=R$.	Increase of resistance per unit produced by stress of 1 grm. per square centim. $=x$.	Increase of resistance per unit which would be caused by stress sufficing to double the length of the wire $=y$.	Increase per unit of specific resistance which would be caused by stress sufficing to double the length of the wire $=z$.
Iron (1)	Annealed . .	1074×10^{-8}	2111×10^{-12}	4·180	2·618
Iron (2)*.	Hard drawn .	1217×10^{-8}	2100×10^{-12}	4·289	2·639
Iron (3)	Hard drawn .	1201×10^{-8}	2197×10^{-12}	3·699	2·057
Piano steel (1) . . .	Hard drawn .	1653×10^{-8}	1910×10^{-12}	3·619	2·081
Piano steel (2) . . .	Hard drawn .	1882×10^{-8}	1831×10^{-12}	3·602	2·084
Platinum (1) . . .	Hard drawn .	..	2233×10^{-12}	3·341	2·239
Platinum (1) . . .	Annealed . .	1434×10^{-8}	2285×10^{-12}	3·404	2·252
German-silver (1). .	Annealed . .	2830×10^{-8}	1501×10^{-12}	1·937	0·107
German-silver (2). .	Annealed . .	..	1545×10^{-12}	2·099	0·345
German-silver (1). .	Hard drawn .	2713×10^{-8}	1892×10^{-12}	2·138	0·138
Copper (1)	Annealed . .	$240{\cdot}8 \times 10^{-8}$	2210×10^{-12}	2·564	0·934
Copper (1)	Hard drawn .	$244{\cdot}0 \times 10^{-8}$	1988×10^{-12}	2·880	..
Copper (3)	Annealed . .	$201{\cdot}4 \times 10^{-8}$	2324×10^{-12}	2·656	1·070
Copper (2)	Annealed . .	$187{\cdot}3 \times 10^{-8}$	2396×10^{-12}	2·918	1·012
Platinum-silver (1) .	Annealed . .	3236×10^{-8}	2346×10^{-12}	2·464	0·624
Platinum-silver (1) .	Hard drawn .	3127×10^{-8}	2437×10^{-12}	2·530	..
Brass (1)	Hard drawn .	834×10^{-8}	2302×10^{-12}	2·275	0·101
Brass (2)	Hard drawn .	$656{\cdot}7 \times 10^{-8}$	2229×10^{-12}	2·203	0·231
Zinc (1)	Hard drawn .	..	4406×10^{-12}	3·379	2·113
Silver (1)	Annealed . .	$161{\cdot}9 \times 10^{-8}$	4272×10^{-12}	3·851	1·531
Silver (1)	Hard drawn .	$173{\cdot}7 \times 10^{-8}$	4561×10^{-12}	3·487	1·703
Aluminium (1). . .	Hard drawn .	$316{\cdot}7 \times 10^{-8}$	1883×10^{-12}	1·260	−0·420
Aluminium (1). . .	Annealed . .	$311{\cdot}3 \times 10^{-8}$	1896×10^{-12}	1·276	−0·262
Tin (1)	Drawn . . .	1166×10^{-8}	10546×10^{-12}	2·920	1·630
Lead (1)	Drawn . . .	2142×10^{-8}	17310×10^{-12}	2·885	1·613

Remarks on Table I.

It will be seen from the above table that the specific resistance of iron is more increased by a given amount of elongation than that of any of the other metals, and that the specific resistance of aluminium is actually *decreased* by stress in the line of flow of the current; this latter fact being signified by a minus sign placed opposite aluminium in the sixth column.

It is also remarkable that the value of z for the alloys, platinum-silver, German-silver and brass should be considerably less than that of their components; and this circumstance, taken in connexion with the comparatively large increase of resistance of iron, would suggest that there is some relation between increase of electrical resistance caused by rise of temperature and that due to mechanical stress.

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* Iron (2), iron (3), steel (1), steel (2), and brass (2) were tested some years ago by a method similar to the one here described.

But the change of resistance attending a given amount of expansion caused by rise of temperature is, in the case of iron, more than a hundred times that resulting from the same amount of expansion produced by mechanical stress; and it is evident that with all metals the alteration of electrical conductivity following on alteration of temperature is due for the most part to other causes than mere contraction and expansion.

Carbon.

As it seemed desirable to extend these researches to as many substances as possible, some experiments were made with carbon rods such as are used for electric lighting purposes. These rods were between 40 and 50 centims. in length, and of different diameters, and their moduli of longitudinal elasticity could be readily determined by holding them in the centre and rubbing them along their length with a resined glove. The note obtained by the longitudinal vibrations, though, of course, very high in pitch, was quite clear and distinct, and very concordant results were obtained when the same pieces were tried at different times. The pitch of the note was determined by the syren, and the following experiment, taken at random out of my note book, will suffice to show what accuracy can be attained with this instrument* even with notes of very high pitch.

Experiment IX.

A carbon rod of length ·496 metre, rubbed longitudinally by means of a resined glove, gave a note, the lower double octave of which was taken on a monochord; the syren was then raised to the pitch of the monochord, and the number of vibrations counted for two minutes at a time.

Number of trial.	Number of vibrations recorded by the syren in two minutes.
1	6860×20
2	6822×20
3	6835×20
Mean . .	$= 6839 \times 20$

In this experiment the monochord was re-tuned at each trial, and it will be observed that the mean value does not differ from any of those forming it by so much as $\frac{3}{10}$ per cent. Of course, by extending the time of each trial and the number of observations, still greater accuracy could have been obtained.

The formula employed for calculating the elasticity is $E = \frac{n^2 \times 4\,l^2 \times \Delta}{9810}$, in which l is

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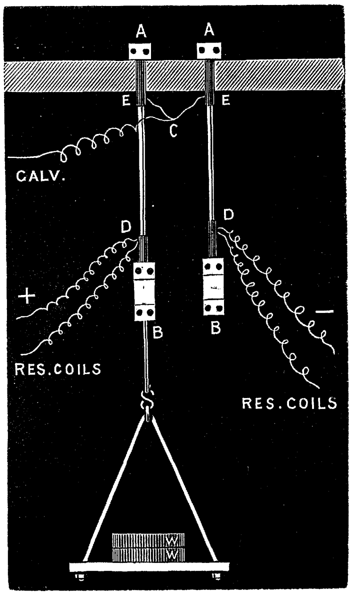
* I have to thank Mr. FURSE, the Curator of the Physical Museum at King's College, for his able assistance in this part of the work.

the length of the rod in metres, n the number of vibrations, Δ the density, and E the elasticity in kilogrammes per square millimetre.

Fig. 9.



In order to determine the alteration of resistance which could be produced by longitudinal traction, the rods were well coated for about 2 inches of their lengths with copper deposited by electrolysis, and were then arranged as shown in fig. 9. The rods passing through two holes in a table were secured at their upper ends by two clamps, A A, and at their lower extremities were fastened two other clamps, B B, either of which would also serve to carry a scale-pan suspended by an iron wire attached to its lower extremity. Two pieces of silk-covered copper wire, about 6 inches in length and $\frac{1}{30}$th of an inch in diameter, were soldered on to the deposited copper at E, and these being also joined together were connected with the galvanometer. Two other pairs of similar wire were soldered at D, and one of each pair was connected, as usual, with the resistance coils, and the other with one pole of the battery. The resistances of the silk-covered copper wires at E, which were small compared with those of the rods themselves, were calculated by determining the resistance of some 6 feet of the wire, and assuming that the resistances of the short pieces at E and the actually determined resistance of the longer piece were proportional to their lengths. The whole table was surrounded on all sides except one with baize, and the mode of proceeding the same as usual. Experiment shows that with the loads employed the alteration of resistance is nearly proportional to the load.

Experiment X.

Carbon rod, length between E and D 45 centims., diameter ·434 centim.

Number of kilogs. in the load.	Number of divisions of the platino-iridium wire through which it was necessary to move the sliding piece in order to restore the balance.	Average alteration of resistance per kilog. in terms of the division of the platino-iridium wire.
2	37·00	18·50
4	74·75	18·69
6	111·80	18·63
		Mean 18·61

In Table II. will be found some data respecting the alteration of resistance produced by loading, the values of "YOUNG's modulus," specific resistance, specific gravity, and section of each rod.

TABLE II.

Number of carbon.	Section in square centims.	Specific gravity water at 4° C = 1 = Δ.	Specific resistance at 15° C.	"YOUNG's modulus" in grammes per square centim. $=e$.	Increase of resistance due to a load of 1 grm. per square centim. $=x$.	Increase of resistance which would be caused by a load sufficient to double the length $=e \times x$ $=y$.	Increase of specific resistance which would be caused by a load sufficient to double the length $=z$.
1	·1411	1·518	4591×10^{-6}	$233{\cdot}8 \times 10^{6}$	11420×10^{-12}	2·470	0·970
2	·1307	1·550	4182×10^{-6}	$264{\cdot}3 \times 10^{6}$	8991×10^{-12}	2·377	0·877
3	·1480	1·552	4483×10^{-6}	$270{\cdot}0 \times 10^{6}$	9535×10^{-12}	2·575	1·075
4	·1351	1·579	3937×10^{-6}	$329{\cdot}0 \times 10^{6}$	8610×10^{-12}	2·835	1·335
5	·1216	1·581	3774×10^{-6}	$279{\cdot}0 \times 10^{6}$	7684×10^{-12}	2·144	0·644
Means	. .	1·556	4193×10^{-6}	$275{\cdot}2 \times 10^{6}$	9248×10^{-12}	2·480	·980

Remarks on Table II.

The sections of the rods were much more uniform than would perhaps have been expected; for example, in the case of No. 3, as measured by a gauge at five points equally apart, the diameter was found to be ·434, ·434, ·434, ·434, and ·433 centim., and the other rods were found to be nearly of the same uniformity as this one.

The specific gravities were determined by breaking the rods into pieces about 5 inches in length and binding a thin copper wire round them, which latter was fastened to a very fine platinum wire, so that the pieces could be weighed in air and in water..

It should be stated that carbon in this form being porous, the specific gravity as usually reckoned will be found to increase if the substance be allowed to remain in water for any time, and especially so if the carbon be boiled in water. The following experiment will show the extent of alteration of the apparent specific gravity :—

Experiment XI.

Several pieces of carbon tied together with fine copper wire, and boiled for five minutes; the pieces then taken out of the hot water, kept for five minutes in cold water, and afterwards suspended by a fine platinum wire in a large vessel filled with water at 15° C.

Weight of carbon in water.	Time after immersion in the large vessel of water, at 15° C.
4·800	5 minutes.
5·020	15 "
5·140	35 "
5·255	75 "
5·291	140 "

The pieces then boiled a second time for 40 minutes, and after having been kept in cold water for 30 minutes, again tested for loss of weight.

Weight of carbon in water.	Time after immersion in the large vessel of water, at 15° C.
5·314	5 minutes.
5·340	45 "
5·393	13 hours.
5·432	5½ days.
5·452	12½ "

As the temperature of the water varied very little during the periods of observation, we see that the apparent specific quantity went on increasing for more than 12 days, and that the total percentage of increase amounted to nearly 12. The specific gravities, however, recorded in the table are calculated from the loss of weight observed shortly after immersion in water, the pieces of carbon not having been boiled, and the section as determined by dividing the loss of weight by the length agreed very well with the section measured by the wire-gauge.

With the exception of number 5, the value of "YOUNG'S modulus" increased very largely as the specific gravity increased; in fact, the value of e is roughly proportional to Δ^8.

BEETZ[*] has also determined the values of e for several carbon rods, used for electric lighting, by longitudinal vibrations, and it would appear from the results obtained by him that $e \div \Delta^8$ is also fairly constant. The mean values of BEETZ' results and my own are given in the next table.

TABLE III.

Specific gravity $=\Delta$.	Value of e in grammes per square centim.	$e \div \Delta^8$.
	BEETZ.	
1·532	$152·0 \times 10^6$	501×10^4
1·547	154·7 „	466 „
1·564	174·7 „	488 „
1·580	193·5 „	498 „
1·593	205·4 „	495 „
1·631	254·8 „	509 „
	Mean value of $e \div \Delta^8 = 493 \times 10^4$	
	TOMLINSON.	
1·518	$233·8 \times 10^6$	829×10^4
1·550	264·3 „	793 „
1·580	304·2 „	783 „
	Mean value of $e \div \Delta^8 = 802 \times 10^4$	

Though, however, $e \div \Delta^8$ is roughly a constant for different specimens of carbon by the same maker, the value of this constant may be evidently very different for samples from different makers, the mean value of BEETZ' samples for $e \div \Delta^8$ being 493×10^4 and that of my own specimens 802×10^4.

The value of e given in Table II. for number 3 is calculated from the formula $e \div \Delta^8 = 802 \times 10^4$.

It will be noticed that the product $e \times x$, *i.e.*, the increase of resistance which would be caused by a load sufficient to double the length of the rod, is nearly a constant for the different specimens, and on referring to Table I. it will be observed that this product is much less than that for several of the metals, though the increase of resistance caused by a stress of 1 grm. per square centimetre is of course, in consequence of the small elasticity of the carbon, greater than any of the metals examined except tin and lead, whose elasticities approach much more nearly to that of this kind of carbon than any of the other substances.[†]

In calculating the alteration of specific resistance it was assumed that $\sigma = ·250$, but

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[*] Ann. der Phys. und Chem., 1881, No. 1, p. 67.

[†] The elasticity of the rods here examined is very nearly equal to that of tin.

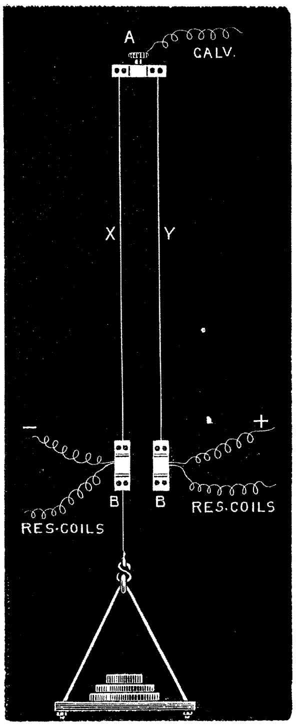
though the values given in the last column of Table II. are in consequence of the want of knowledge of σ approximate to the true ones, they must be sufficiently so to prove that not only is the total resistance of the carbon increased by loading but so also is the *specific resistance.*

The mean value of the specific resistance of the different specimens is 4193×10^{-6}, and is therefore more than 100 times greater that the corresponding number for platinum-silver, which latter metal ranks highest in the list of metals in Table I.

NICKEL.

Through the kindness of Messrs. JOHNSON and MATTHEY, who after some difficulty succeeded in drawing for me two pieces of almost pure nickel wire 8 feet in length, I was able to make some experiments on this metal, in which I obtained results so completely differing from those observed in the case of the other substances, that I may perhaps be excused for treating them in some detail.

Fig. 10.



The metal when first received was in the hard drawn condition, and in this state was tested for torsional rigidity and longitudinal elasticity, for the former in the usual manner and for the latter by longitudinal vibrations. The pieces were then suspended in the air chamber, and since it was not thought desirable to bend the wire, the following arrangements were made, which are sufficiently shown in fig. 10.

X and Y are the two wires to be compared, the clamp A rests as before on the top of the air chamber, and of the two clamps B B fastened to the lower ends of X and Y one has a stout iron wire attached to it for the purpose of a suspension for the scale-pan. Also to each of the clamps B are soldered two silk-covered copper wires $\frac{1}{40}$th of an inch in diameter and 3 feet in length, one of these serving to connect the clamp with one of the battery wires and the other with the caoutchouc-covered wire leading to the resistance coils. The wires X and Y were each $3\frac{1}{2}$ feet in length, but were not cut off from the 8 feet pieces, the remainder of the wire* being allowed to hang down on the outside of the air chamber, whilst the silk-covered copper wires fastened to the clamps B B were brought down through the hole in the table at the bottom of the air-chamber. When the experiments on the hard-drawn wire had been finished, the metal was well annealed and similar ones made on it in this new state, with this difference, however—that now the wire X was tested with larger and larger loads until it finally broke. The results of the experiments made on the wire in the hard drawn and annealed conditions will be found in Table IV.

The curves in Table V., showing the temporary alteration of resistance produced in the annealed wire by different loads after the wire had been previously stretched for some time with weights of 16, 18, 20, 22, and 24 kilogs., are drawn with their abscissæ to represent the percentage alteration of resistance on a scale of ·0025 to the millimetre, and with their ordinates the number of kilogrammes per square centimetre in the load on a scale of 25 kilogs. to the millimetre.

TABLE IV.

Condition.	Section in square centims.	Specific gravity at 20° C., water at 4° C. = 1.	Specific resistance at 20° C.	Torsional rigidity in grms. per square centim. = r.	"YOUNG'S modulus" in grms. per square centim. = e.	Ratio of lateral contraction to elongation.
Hard drawn	·005832	8·7066	1757×10^{-8}	$723{\cdot}5 \times 10^{6}$	$2270{\cdot}6 \times 10^{6}$	·570
Annealed .	·005832	8·7386	1736×10^{-8}	$758{\cdot}5 \times 10^{6}$	$2174{\cdot}6 \times 10^{6}$	·433

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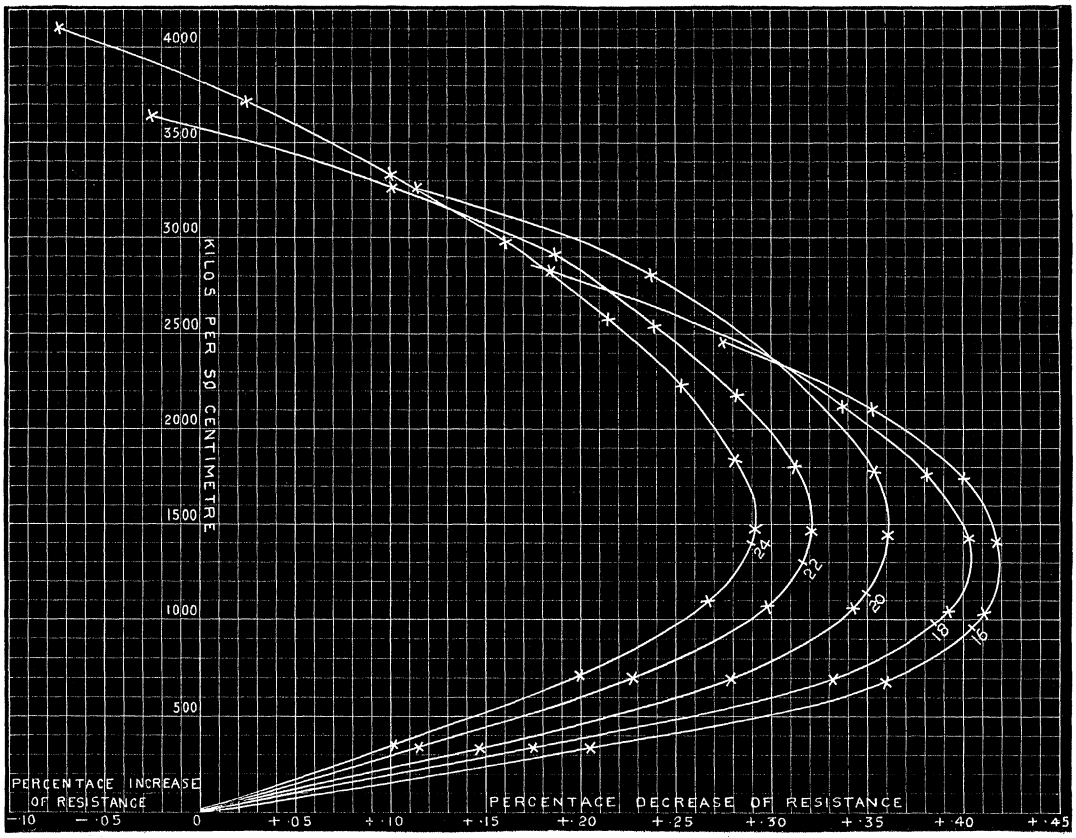
* Not shown in the figure.

TABLE V.—Curves showing the temporary alteration of electrical conductivity of nickel wire produced by longitudinal traction at the temperature 22° C.



Remarks on Tables IV. and V.

One of the first points to notice in Table IV. is the large value of "YOUNG'S modulus," which for both the hard drawn and the annealed conditions of the nickel exceeds the highest values obtained for pianoforte steel wire.

Again we have seen in Part I. that the value of "YOUNG'S modulus" increases as the mean distance between the molecules diminishes, and the ratio of the specific gravity to the atomic weight of nickel, which is inversely as the cube root of the mean distance between one molecule and another, is ·1493, whilst that of iron, which with copper has the ratio higher than is the case with any of the other metals mentioned in this paper, is ·1386. We have also seen that $e \times \alpha^7$ is roughly a constant for the different metals, where α is the mean distance between one molecule and another, and e is the value of "YOUNG'S modulus;" in the cases of nickel and iron this product is $\cdot 1838 \times 10^{12}$ and $\cdot 1993 \times 10^{12}$ respectively.

The ratio of the lateral contraction to the linear elongation obtained from the formula $\sigma=\frac{e}{2r}-1$ of the hard drawn nickel is of course impossible, as was the case, it will be remembered, with the value of σ with hard-drawn copper, brass, German-silver, and platinum-silver, and the wire therefore furnishes another proof that the formula cannot be applied to hard drawn metal.

The most remarkable feature, however, presented by nickel is that shown in Table V., where we learn that the resistance is absolutely *decreased* up to a certain extent of loading and then begins to increase. We see, moreover, that the *maximum decrease* becomes less and less as the wire receives more and more permanent extension, and that the point of loading where this maximum occurs gradually rises with the amount of permanent extension.* As might be supposed, therefore, the decreases of resistance obtained with two loads of 3 and 6 kilogs. were with the hard drawn metal much less than with the annealed one. Again, if we take the average decrease of resistance produced by a load of 1 grm. per square centimetre between the points of zero load and the load producing maximum decrease, we find it in the case of the outer curve to be 3216×10^{-12}, and the product of this number by $e=6{\cdot}994$, whilst the decrease of *specific* resistance attending unit increase of length, or the number corresponding to z in Table I., would amount to 8·860. All these numbers, especially the last, are very considerably greater than the corresponding *increases* of resistance obtained with any of the other metals. We thus observe that whether we regard the peculiarity of loading up to a certain point producing decrease of resistance, and after this point increase, or the comparatively enormous temporary variations of resistance produced by loading, nickel stands by itself, and the idea at once suggested itself that this abnormal behaviour of the metal might be due to the influence of circular magnetization caused by the current employed in balancing the wire and the comparison-wire. Accordingly two experiments were made of the following nature:—First, as the alteration of resistance might be only apparent and due to the fact that VILLARI's shock-currents were not the same in the stretched and unstretched wires,† both the galvanometer circuit and the battery circuit were kept closed, and the position of the light on the scale noted with different stretching weights: the readings taken in this way gave alterations of resistance which were exactly the same as those obtained by the usual method. Secondly, as the alterations might be really those of resistance, but due to the fact that circular magnetization, might‡ cause an alteration of resistance in both iron and nickel, and unequally in the stretched and unstretched wires, the resistances in the bridge were so adjusted that currents of one-half and one-fourth respectively of the current which had previously

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* The numbers 16, 18, 20, 22, 24, on the curves represent the load which had previously been on the wire before testing for the temporary effect of loading.

† I did not think this likely, as I had not been able to detect anything of the kind when iron wire was used.

‡ According to AUERBACH, but not according to experiments tried by myself.

passed through the wire in determining the resistance might now do so; but again the alterations of resistance were found to be the same as before.* Now if E denote the electromotive force of the LECLANCHÉ, x and y the resistances of the wire and the comparison-wire, α and β the resistances in the box, and B the resistance of the battery and connexions, the current in x will be proportional to $\frac{E}{B(1+\frac{x+y}{\alpha+\beta})+x+y}$, or since x and y were only ·44 ohm each, whilst α and β were 100 ohms each, the current in x will be nearly proportional to $\frac{E}{B+x+y}$.

E was nearly 1·5 volts, and $B+x+y$ in the case of the weakest current was made 10 ohms; therefore this current would in absolute measure of C.G.S. units be ·015. Unless, therefore, the maximum difference of alteration of resistance caused by circular magnetization in the stretched and unstretched wires had been reached by a still smaller current than this, we cannot regard the curious behaviour of nickel in respect to the effect of stress on its electrical conductivity as due to circular magnetization.

Again, another idea suggested itself, namely, that the wires being suspended vertically might cause the resistance of the stretched and unstretched wires to be altered unequally by the earth's vertical magnetic force, but this latter, it will be seen, is of too small intensity to have any effect at all comparable with that observed in the stretching; and, moreover, experiments subsequently made with the wire at right angles to the magnetic meridian, showed plainly that this was not the case. We must therefore regard the abnormal effect produced on the electrical resistance of nickel as not due to the earth's magnetic force.†

We have seen also that, in the case of other metals which have suffered permanent extension, rest increases the elasticity and *diminishes* the temporary *increase* of resistance which any load is capable of causing, and that with iron this effect is very apparent. It was therefore an interesting point to determine whether the *decrease* of resistance which moderate loading produces in nickel would be increased by rest. The next experiment shows that this is so.

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* Similar experiments with iron had also previously shown that with this metal there is no appreciable difference in the alteration of resistance produced by stretching when different current strengths are employed in the bridge.

† After these experiments I re-tried iron with a view to ascertain whether *very small loads* might not produce decrease of resistance, but found that the smallest load that caused any effect whatever produced as before increase of resistance.

Experiment XII.

An annealed nickel wire loaded and unloaded several times on three different occasions, with weights of 18, 20, and 22 kilogs. respectively, and then tested with equal or lesser loads.

Load in kilogs. put on and off several times $= \alpha$.	Load used in testing after $\alpha = \beta$.	Temporary alteration of resistance produced by β. − Decrease of resistance. + Increase of resistance.	Time after using α at which β was applied.
18	First 8 . . .	−89	½ hour.
	Next 10 . . .	. .	
	First 8 . . .	−95	1 "
	Next 10 . . .	+60	
	First 8 . . .	−99	24 hours.
	Next 10 . . .	+57	
20	First 8 . . .	−79	½ hour.
	Next 12 . . .	+71	
	First 8 . . .	−82·5	7 hours.
	Next 12 . . .	+67·5	
22	First 8 . . .	−72·0	½ hour.
	Next 12 . . .	+64·5	
	First 8 . . .	−73·5	12 hours.
	Next 12 . . .	+62·5	

We see here that rest produces a very appreciable effect, increasing the negative alteration of resistance and diminishing the positive alteration; but we notice also that as the loads α become larger and larger the influence of rest becomes less and less marked; and, lastly, that as α increases to nearly the breaking load of the wire the effects both of the moderate load to produce decrease and of the excessive load to produce increase become more and more equal, and if we turn to Table V. we see plainly that the points in the curves showing the position of maximum decrease of resistance, which at first become wider and wider apart, at length begin to close up.

All this is intelligible if we bear in mind what has been proved in Part I., namely, that the elasticity of all metals is diminished by permanent extension carried to a certain point, and beyond this point increased, and provided that we assume that *temporary*[*] elongation without regard to the stress producing it causes increase of resistance. The question then naturally arises, do stress and the consequent temporary strain produce on the electrical conductivity of substances opposite effects?

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[*] Permanent elongation we shall find produces in most metals first increase of specific resistance and then decrease, but in iron and nickel first decrease and then increase.

Influence of Permanent Extension on the Temporary Alteration of Resistance caused by Longitudinal Stress.

It has been asserted in Part I. that the elasticity of a wire is diminished by permanent extension not exceeding a certain limit. In order to furnish still further evidence in favour of this assertion some experiments were made on the influence of permanent extension on the temporary alteration of resistance produced by longitudinal stress.

Experiment XIII.

A piece of copper (3) was subjected to loads which were gradually increased, and after the removal of each load the temporary alteration of resistance was determined from the mean values got by testing with from one to five measures of water.

Number of measures used for the permanent extension.	Number proportionate to alteration of resistance of wire.	Difference between consecutive alterations of resistances.	Number proportionate to temporary alteration of resistance caused by stress of 1 grm. per square centim.	Difference between consecutive alterations of resistance.
5	860	. .	644	. .
6	862	2	648	4
7	865	3	652	4
8	878	13	658	6
9	912	34	681	23
10	952	40	692	11
11	985	33	693	1

Experiment XIV.

A similar piece of wire was loaded with from 12 to 14 measures of water, and after the removal of each load tested in a similar manner to the above.

Number of measures used for the permanent extension.	Number proportionate to alteration of resistance of wire.*	Difference between consecutive alterations of resistances.	Number proportionate to temporary alteration of resistance caused by stress of 1 grm. per square centim.	Difference between consecutive alterations of resistance.
12	1288	. .	421	. .
13	1418	130	416	−5
14	1574	156	409	−7

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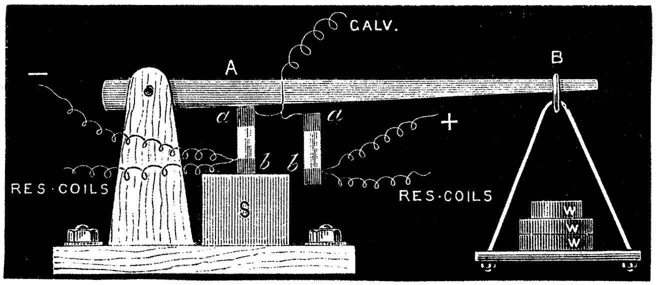
* Neither these numbers nor those in column 4 are on the same scale as the corresponding numbers in the last experiment.

The last two experiments show that with copper the temporary alterations of resistance caused by longitudinal stress increase up to a certain limit of permanent extension and then begin to decrease. We also see that the greatest changes in the values of the temporary alterations of resistance take place at those places where there are the greatest permanent changes of resistance.

The Effect of Compression on Electrical Conductivity.

It was anticipated that compression would in most cases produce decrease of electrical resistance, and as carbon seemed a suitable substance to experiment on, the following arrangement was made with the view of ascertaining whether compression would produce on the resistance of carbon the opposite effect to that caused by longitudinal extension:—S in fig. 11 is a block of stone on which rests upright the piece of carbon which it is desired to compress; the other piece of carbon to serve as the comparison-piece is supported near the first by a clip-stand (not shown in the figure). The two pieces of carbon were each about 4 inches in length, and were well coated with copper deposited by electrolysis for a distance of about three-quarters of an inch at the ends. To the upper ends *a*, *a* were soldered two silk-covered copper wires as in the experiments on extension, and the junction of these was connected with the galvanometer, whilst to the copper deposited on the lower extremities *b*, *b* were soldered wires to serve for connecting with the battery and resistance coils. The compression was produced by putting weights into a scale-pan attached to the end B of a lever of hard wood, which in the position of the carbon rod produced on the latter a pressure five times that of the weights in the pan.

Fig. 11.



Experiment XV.

A piece of carbon rod, 4 inches in length and ·1386 square centim. in section, was compressed by putting a weight of 2 kilogs. on to the pan at the end of the lever.

Number of trial.	Alteration of resistance as represented by the number of divisions of the platino-iridium wire through which it was necessary to move the sliding-piece in order to balance the effect of putting on or taking off 2 kilogs.
1	118·0
2	118·5
3	110·0
4	115·5
Mean	115·4

From the results of Experiment XV. it was calculated that a compression of 1 grm. per square centimetre would cause a *decrease* of resistance of 6398×10^{-12} per unit, and as the longitudinal elasticity was $267{\cdot}2 \times 10^{6}$, the alteration of resistance attending an amount of compression which would suffice to halve the length of the rod would be 1·710, and of this alteration ·210 would be in the specific resistance of the rod. The specific resistance of the specimen at 15° C. was 4214×10^{-6}.

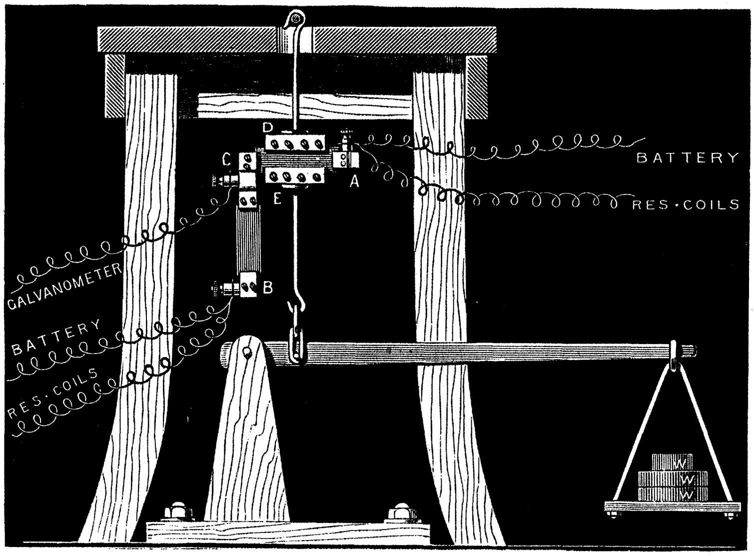
We see that the effect of compression is to diminish both the total resistance and the specific resistance of the specimen of carbon, and is therefore of an opposite nature to that of longitudinal extension.

THE ALTERATION OF ELECTRICAL CONDUCTIVITY PRODUCED BY STRESS APPLIED IN A DIRECTION TRANSVERSE TO THAT OF THE CURRENT.

It has been seen that, in the case of most metals, stress applied in the same direction as that of the current increases, both permanently and temporarily, the resistance, and it seemed probable that stress when applied in a direction perpendicular to that of the current would alter the resistance in the opposite direction. The following arrangements were therefore made with the view of testing this point:—

Strips of metal foil about 10 centims. long, 2 centims. broad, and ·01 centim. thick, were arranged in pairs as in fig. 12. D and E are stout brass clamps into which two hooked iron rods are screwed, and the strip to be examined is clamped into the brass pieces, which are 8 centims. in length, but insulated from them by means of silk. The clamp C connects the metal to be tested with a similar strip, and both strips with one terminal of the galvanometer; whilst the clamps A and B serve, as before, to connect the strips with the resistance coils and battery.

Fig. 12.



The strip to be examined was strained by means of a stout wooden lever, and the table which supported the upper hooked iron rod was surrounded with baize.

Experiment XVI.

A strip of iron foil, 10 centims. in length, 2·1 centims. in width, and of specific gravity 7·65, was subjected to a stress of 120 kilogs., and after two or three applications and removals of this load, it was found that this stress produced a *diminution of resistance* which required the sliding piece to be shifted through 20 divisions of the platino-iridium wire, and that on the removal of the stress the resistance was increased by the same amount. The load was distributed over a sectional area of ·098 square centim., and the diminution of resistance, which would be caused by a stress of 1 grm. per square centimetre, was calculated to be $123{\cdot}6 \times 10^{-12}$ per unit. Inasmuch, however, as only one-third of the total resistance measured was effected by the stress, it was assumed that if the whole of the piece could have been strained to the same extent the diminution would have been 371×10^{-12}; whereas in the case of iron *wire* subjected to longitudinal traction the alteration of resistance produced by the same stress amounted to 2111×10^{-12}, or nearly six times as much as that caused by transverse traction. Again, if we assume that the value of "YOUNG's modulus" is the same for the foil as for the wire, the total alteration of resistance caused by the transverse traction which would suffice to double the width of the strip would be ·742 per unit. Also taking the ratio of lateral contraction to elongation to be ·281, as was the case with iron (1), the total decrease of resistance due to mere change of form would be 1·562 ; and therefore on the whole there would seem to be an *increase of specific resistance* of ·82, caused by stress sufficing to double the width of the strip.

Experiment XVII.

A strip of tin-foil of nearly the same dimensions as the iron-foil used in the last experiment was tested with a load of 8 kilogs., and a permanent decrease of resistance thereby produced = ·001 per unit; a temporary decrease of ·002 per unit was caused by the application of the load, and it was calculated that the temporary decrease per unit effected by a stress of 1 grm. per square centimetre would amount to 2581×10^{-10} as compared with 1055×10^{-11}, the alteration caused by the same amount of longitudinal stress with tin wire. It would thus seem that, contrary to what takes place with the iron, the alteration produced by transverse traction is much greater (about 23 times as great) than that caused by longitudinal traction; and if we suppose the elasticity of the foil to be even much less than that of the wire, there must be a very appreciable *decrease of specific resistance ;* this latter, if the values of e and σ are the same for the foil and the wire, would be 70·0 per unit, *i.e.*, the metal would have a specific resistance of $\frac{1}{70}$th of its original specific resistance, if stress were applied transversely, sufficing to double the width of the foil. The corresponding alteration produced by the same amount of stress applied longitudinally to a wire of tin is, as we have seen, less than 2 per unit.

Experiment XVIII.

A strip of zinc-foil of nearly the same dimensions as the strips of iron and tin last used was tested with loads varying from 50 to 100 kilogs. A stress of 50 kilogs. produced a permanent decrease of resistance amounting to ·0091 per unit, 70 kilogs. a decrease of ·02 per unit, and with 100 kilogs. the foil was partly pulled away from the clamps ; before this, however, the temporary decrease of resistance produced by 50 kilogs. was ascertained to be ·028 per unit. After the accident the foil was securely reclamped, and now three trials with 50 kilogs. gave alteration of temporary resistance amounting to ·010, ·017 and ·010 respectively, the load in the second of the three trials having been allowed to remain for a longer period on the foil than was the case in the other two trials. It was then evident that the time during which the load was allowed to remain on the foil largely influenced the temporary alteration of resistance, and accordingly several experiments were made with a view to verify this fact, which was eventually abundantly established. In one of these experiments a load of 70 kilogs., after having been put on and taken off several times, was allowed to remain on for 10 minutes, when a decrease of ·0428 per unit was measured; after 20 minutes the decrease amounted to ·0557 per unit, part of the decrease produced after the first 10 minutes was permanent, but a considerable part was temporary.

The foil was now tested with loads of 12 and 20 kilogs., the latter causing a decrease of resistance represented by 300 divisions of the platino-iridium wire, and the former 180, that is, the decrease was exactly proportional to the load. From these results it was calculated that a transverse stress of 1 grm. per square centimetre would produce a decrease of resistance amounting to 12384×10^{-11} as against 4406×10^{-12}, the alteration caused by the same longitudinal stress in a zinc wire; the alteration in the former case is about 28 times that in the latter. Again, assuming that the values of e and σ are the same for the foil as for the wire, the decrease of specific resistance which would be caused by transverse strain sufficient to double the width of the strip would be 95 per unit; whilst the alteration for the same amount of longitudinal stress is about 2 per unit. The temporary decrease of resistance of zinc and tin appeared to be so very large, that it was suspected that the silk did not properly insulate the foil from the upper and lower clamps; but this did not seem to be the case, as the resistance was the same before and after clamping; nor could the stress have temporarily impaired the insulation, as if so the same large decrease would have been obtained with iron. It would thus appear that, at any rate for the metals zinc and tin, the effect on the electrical resistance of stress perpendicular in direction to the line of flow of the current is the reverse in every respect of that of stress applied longitudinally. In the case of iron we have seen that though the resistance is on the whole decreased, the mere change of form would more than account for the decrease; and that unless the amount of lengthening which any given load per square centimetre can produce is much less with iron-foil than with iron wire the specific resistance is increased.

One of the most remarkable features of these experiments is the large influence of time on the temporary alteration produced by the heavy loading of zinc and tin. A similar influence, though not to the same extent, was noticed with aluminium, zinc, and tin when great longitudinal stress was employed, and with these metals also for both directions of stress, the departure from proportionality between the load and the alteration produced thereby became very marked, though here again much more so when transverse than when longitudinal stress was applied.

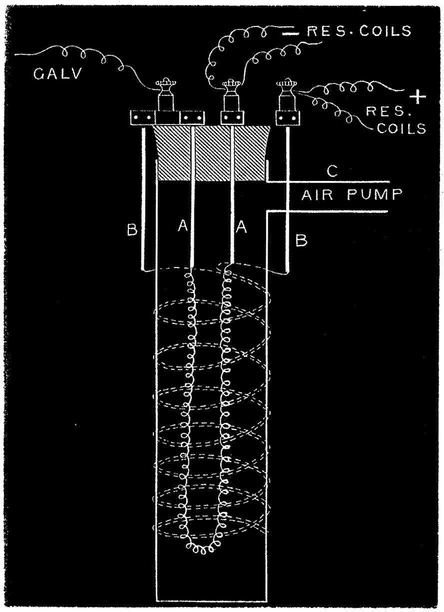
THE ALTERATION OF ELECTRICAL CONDUCTIVITY PRODUCED BY STRESS APPLIED EQUALLY IN ALL DIRECTIONS.

Unsuccessful attempts and mode of determining the lowering of the melting-point temperature of ice.

So far back as the winter of 1877 I attempted to detect and measure the effect on the electrical conductivity of wires produced by such alterations of fluid pressure as could be obtained by means of the air-pump only, being under the impression at that time that the change of conductivity caused by rise of temperature was due for the most part to mere expansion.

In the first attempt the wire to be tested, a silk-covered copper wire about 12 feet in length and $\frac{1}{40}$th of an inch in diameter, after having been well soaked in melted paraffin wax was coiled in a spiral and placed in a thin, hollow, brass tube (fig. 13), having an inner diameter of 2·8 centims. and a length of 15 centims.

Fig. 13.

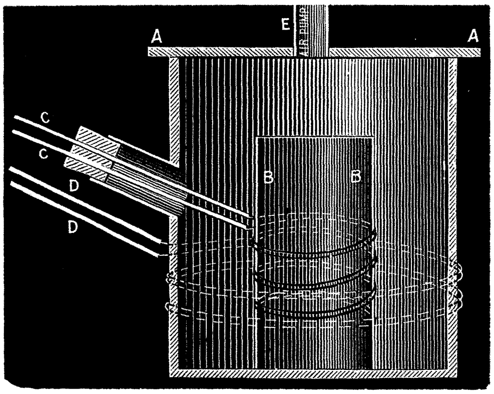


The ends of the wire were soldered to two stout copper wires A A, which passed air-tight through an indiarubber cork and served to connect the wire under examination with the comparison-wire. The latter having its ends soldered to the two stout copper wires B B, was wound double round the outside of the hollow cylinder, and was, together with B and B, secured to the cylinder by string; the comparison-wire had also been soaked in melted paraffin wax, and the four stout wires, A, A, B, B, and their junctions with the other wires, well coated with shellac varnish. The two wires, which as usual were of the same dimensions and substance, were joined up with the other parts of the bridge in the manner already described, and the tube C served to connect the cylinder with an air-pump and barometer-gauge. The whole arrangement having been placed in a box the cylinder was well packed up in sawdust, and after a sufficient time had been allowed to elapse to enable the temperature of the wires to become constant the experiments began.

This plan entirely failed, the effect of the alteration of pressure on the resistance of the wire being completely masked by the change of temperature caused by the rarefaction or condensation of the air even when a considerable time had been allowed to elapse. The condensation and rarefaction of the air would cause a change of resistance the opposite to that looked for as the result of change of pressure; and so slowly did the temperature alter after the first half-hour that I began to suspect that *increase of pressure caused increase of resistance*, and for some days actually tried to measure the *increase* of resistance apparently caused by increase of pressure. Finding, however, that the observations did not agree sufficiently with each other I filled the cylinder with water and immersed it in a large glass vessel, also filled with water, which was stirred from time to time. This plan also failed, the compression of the water causing an effect in the same direction though not to the same extent as the compression of the air had done. It was noticed, however, that after the air was let into the vessel there was *no change of resistance till a second or so afterwards.*

Finally, the following method was adopted:—The vessel containing the wire to be tested consisted (fig. 14) of a brass cylinder closed at one end, and which could be closed at the other by a brass cover A A. The vessel was about 7 inches deep and 6 inches in internal diameter; the open end and the cover which closed it having been carefully ground, so that with the help of a little grease it could be made perfectly air-tight. The wire under examination was wound double on the outside of a very thin brass cylinder B B, and the ends of the wire were soldered to the stout copper wires C, C, which latter passed through an indiarubber cork, fitting air-tight into a tube about 1 inch in diameter, which was soldered into the vessel and made an angle of 45° with the side. The comparison-wire was wound double round the outside of the large cylinder, and the two stout copper wires D, D, to which the

Fig. 14.



ends of the wire were soldered, were connected in the same way as before with C, C and the other parts of the bridge. The whole arrangement of wires and cylinders was placed in a wooden box having holes cut in one of the sides to admit of the connexions C, C and D, D passing through, and this box was in turn placed inside a larger one, so that the space between the two boxes could be filled with sawdust.

The mode of proceeding was as follows:—First, ice broken into small pieces was packed into a layer about 3 inches thick round the larger of the two cylinders, then, after an interval of about half-an-hour, both the large cylinder and B were filled with pounded ice, the cover put on, and over it placed a large sheet of paper containing sawdust. The tube E served to form by means of indiarubber tubing connexion with the air-pump, and after a sufficient time had been allowed to make the balance of the two wires constant the experiments began.

This plan seemed to act admirably. A short time after exhausting the air there seemed to be an increase of resistance, and on letting in the air again a decrease. After each operation with the air-pump the wires were tested at intervals of 10 minutes, until it was certain that the full effect on the resistance of the alteration of the pressure had been produced. Each experiment lasted more than one hour, and it was only possible to make two or three experiments before the ice had to be readjusted round the wires; as evidently after some three hours, though there might be no appreciable melting of the ice, the galvanometer showed that one or other of the wires was not quite at the temperature of the ice. The following are the results obtained:—

Experiment XIX.

Alteration of resistance represented by the number of divisions through which it was necessary to move the sliding-piece in order to restore the balance.	Alteration of pressure in millimetres of mercury.
12·35	700
13·28	721
13·00	730
12·40	718
13·20	710
12·44	707
13·46	707
12·44	707
12·84	708
12·64	708
11·32	708
13·76	708
12·74	707
12·74	707
12·74	707
12·74	710

In these experiments, the divided wire was of German-silver, each division being equal to ·00021105 ohm at the temperature of the room, and since 100 ohms were used at each end of the wire, the alteration of resistance represented by moving the sliding-piece over one division of the wire would equal $\frac{1}{\cdot 000001055}$ of the whole, the effect of one-tenth of a division was readily perceptible, and the second place of decimals in the above columns were got by taking the mean of several observations at each pressure. From the above results it was calculated that the decrease of resistance per unit produced by an increase of fluid-pressure of 1 grm. per square centimetre would be 27854×10^{-12}.

On showing these results, however, to Professor G. G. STOKES, he suggested that sufficient account had not been taken of the fact that the alteration of pressure might affect the resistance by altering the melting-point temperature of the ice, though, as I thought, the ice would not be sufficiently wet in the inner cylinder, as the temperature of the room at the time was frequently almost at 0° C., and the cylinder well surrounded by ice on the outside to affect the result in this way. Nevertheless, acting on this suggestion, I carefully determined the increase of resistance at 0° C. for a rise of 1° C., in the manner adopted by MATTHIESSEN, and found this to be ·0038587 per unit of resistance. Now, J. THOMSON was led by theoretical considerations* to the conclusion that the melting-point temperature of water would be lowered ·0075° C. by an increase of one atmosphere of pressure, and the matter was put to experimental test by W. THOMSON, who arrived at results agreeing almost exactly with this conclusion. If we assume one atmosphere to be equal to 76 centims. of mercury, or 1034 grms. per square centimetre, the lowering of temperature produced by a pressure of 1 grm. per square centimetre on the melting-point of ice should be ·00000725° C. Now, if the alteration of resistance was entirely due to change of temperature in the melting-point of the ice, my experiments would give a lowering of temperature for a pressure of 1 grm. per square centimetre equal to $\frac{278 \cdot 54 \times 10^{-10}}{\cdot 003859}$, *i.e.*, to ·00000723° C.

This result then led me to believe that either there was no change of resistance produced by the pressure merely, or, as subsequently proved to be the case, that the alteration of pressure was too small to produce an appreciable effect even with the very delicate galvanometer which I was using. I also remembered that, when water had been employed, as in the previous experiment, as has been before mentioned, there was no appreciable effect *immediately* after the air had been let into the vessel. Moreover, I called to mind that on two occasions when the temperature of the room was almost exactly 0° C. there was no effect, when, as in the last experiments, ice had been used, *even for some* 10 *or* 20 *minutes* after using the pump; but in this case I had attributed the absence of effect to the regelation of the ice over the cylinder

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* Trans. Roy. Soc. Edinburgh, Jan., 1849. Cambridge and Dublin Math. Journal, Nov. 1850.

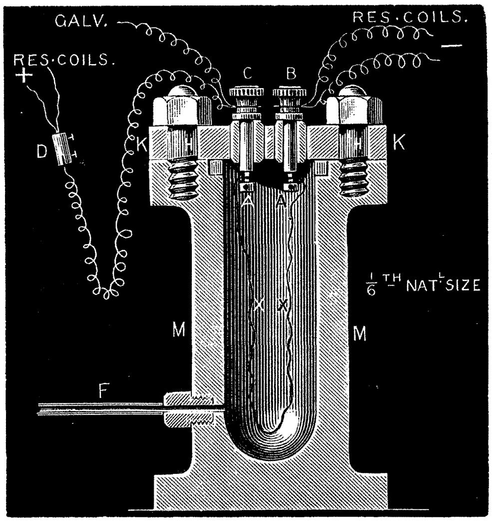
round which the wire was wrapped, and had taken the trouble several times to take off the cover and loosen the ice. I have now no doubt that the warmth of the hand in this last act had melted the ice sufficiently to allow the alteration of the melting-point temperature to be felt.

Though these experiments were failures as far as the immediate object in view was concerned, they show what a delicate and accurate thermometer the galvanometer can prove, and that an interesting investigation of the lowering of the melting-point temperature of ice* could be made by using a modification of the above apparatus suitable for pressures of two or three hundred atmospheres, such as will be described presently.

SUCCESSFUL ATTEMPTS AND RESULTS.

The previous trials having shown that pressures of several atmospheres must be resorted to if one was to hope to measure any alteration of resistance which might be produced by fluid-pressure, the following apparatus (fig. 15) was employed :—

Fig. 15.



M M is a strong vessel made of gun-metal (drawn to scale in fig. 15 one-sixth of the real size), C, B are two binding screws at the ends of two stout brass wires passing water-tight through a cover, K K, and separated from the latter by insulating material. This cover could be removed at will, and the ends of the wire to be tested, X, X, connected by two small binding screws (shown in the figure unscrewed) A, A, at the lower ends of the stout brass wires. After the wire had been well secured to A and A, these latter, the wire itself and those portions of the stout brass wires which projected below the cover, were well coated with paraffin wax. The vessel having been filled with

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* The effect on the resistance of the wire is so very small as to be almost neglectable, and the correction even for this can be made by data which are given further on. (See p. 77, Table VI.).

water, the cover with the wire suspended from it was put on and secured by means of three screws and nuts, two of which, H, H, are shown in the figure, the cover having been made to fit water-tight under the highest pressures employed, by means of a gutta-percha collar. The wire X and the comparison-wire were then connected up in the usual way, as shown in the figure,* and the whole well-covered with baize.

The first wire which was tried was a piece of the copper wire used in the last experiments, and a day having been selected at which the temperature was about 4° C., pressure was put upon the wire by means of a force-pump which formed part of a hydraulic press.† The pump communicated with the vessel by means of the tube F, and was capable of supplying a pressure of upwards of 5000 lbs. on the square inch. The pressure was measured by a strong spring pressure-gauge, divided so as to read to a pressure of 100 lbs. on the square inch.

On working the pump so as to increase the pressure there was, after a short time, a very decided decrease of resistance perceptible, and on removing the pressure the resistance returned to almost its former value. Several attempts were made with greater and greater pressures, which were carried up to 4000 lbs. on the square inch, and all gave indications in the same direction ; but unfortunately, on raising the pressure to 5000 lbs. on the square inch, the insulating substance round one of the stout brass wires cracked, and allowed the water to come through the cover. As these trials were only intended to be preliminary, no measurements had been taken of the alteration of resistance produced, but there was now no question that in the case of copper wire increase of pressure produced decrease of electrical resistance.

These experiments could not be renewed till the following winter, when the flaw mentioned above having been repaired, some fresh trials were made with iron wire and the following measurements taken :—

Experiment XX.

Pressure in lbs. per square inch.	Number of divisions of the platino-iridium wire through which it was necessary to move the sliding piece in order to restore the balance.
900	20·0
1100	37·7
1300	25·0
Mean 1100	Mean 27·6

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* In the actual experiments X was secured to the vessel by string, the connexions having been well insulated by wrapping them up in paper.

† This pump was lent to me by the Rev. T. A. Cock, of King's College, who kindly had it put into complete working order before I used it.

These results give an alteration of 1160×10^{-12} per unit in the resistance for a pressure of 1 grm. per square centimetre, and as in the case of copper increase of pressure produces diminution of resistance.

The experiments were again put an end to by a flaw in the insulation, which was made on attempting to carry the pressure to a greater extent, and therefore the final result can only be considered as very roughly correct. Fortunately, however, there is a means of testing approximately the accuracy of this result, as it was found that at the temperature of the room (about 4° C.) the heat caused by the compression of the metal exactly balanced the effect of the pressure on the wire—so exactly, indeed, that even when pressures of 3000 lbs. per square inch were employed, *the instant after the removal of the pressure there was no change whatever in the resistance,* but in a few seconds afterwards the resistance began to decrease, and apparently attained a minimum in about half an hour. About this fact there can be no doubt, as it was repeated several times and with several different pressures. Now the change of temperature produced by an alteration of fluid pressure amounting to 1 grm. per square centimetre is for any substance equal to $\frac{T \times \alpha}{J \times x}$, where T= the absolute temperature, α the coefficient of cubical expansion, J JOULE'S equivalent, and x the specific heat referred to unit volume. In this case $T=278$, $\alpha = \cdot 0000342$, $J=42{,}400$, $x = \cdot 842$ at the temperature 4° C.

Therefore the rise of temperature caused by an increase of pressure of 1 grm. per square centimetre would be ·000000264° C.; and since the increase of resistance of the wire for 1° C. at 4° C. had by preliminary experiments been determined to be almost exactly ·0047 per unit of resistance, the increase of resistance due to the heat of compression would be $\cdot 000000264 \times \cdot 0047$, or 1241×10^{-12}—a result which agrees fairly with that arrived at by direct experiment.

After making these experiments I was glad to find that CHWOLSON had succeeded in measuring the effect of fluid pressure in the cases of copper, lead, and hard brass,* and with these three metals observed that increase of fluid pressure produced decrease of electrical resistance.

In the next table are given the results of CHWOLSON'S and my own experiments, in centimetre gramme units.

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* Im. Acad. of St. Petersburg Bull., March, 1881, and 'Nature,' June 2, 1881, p. 112.

TABLE VI.

Name of Metal.	Decrease of resistance per unit produced by an increase of fluid pressure of 1 grm. per square centim. = A.	Increase of resistance per unit produced by a longitudinal tension of 1 grm. per square centim. = B.	Ratio of B : A.	Decrease of resistance per unit attending a fluid pressure sufficing to halve the length of the wire.	Increase of resistance per unit attending longitudinal tension sufficing to double the length of the wire.	Decrease of specific resistance per unit attending a fluid pressure sufficing to halve the length of the wire = C.	Increase of specific resistance per unit attending longitudinal tension sufficing to double the length of the wire = D.	Ratio of C : D.
Lead . .	10638×10^{-12}	17310×10^{-12}	1·63	2·440	2·885	3·440	1·613	2·14
Copper .	$1257·0 \times 10^{-12}$	$2310·0 \times 10^{-12}$	1·84	3·470	2·713	4·470	1·005	4·45
Iron . .	$1160·0 \times 10^{-12}$	$2111·1 \times 10^{-12}$	1·82	5·269	4·180	6·269	2·618	2·39
Brass .	$1064·0 \times 10^{-12}$	$2265·5 \times 10^{-12}$	2·13	3·004	2·239	4·004	·166	2·41
Means .	. .	. .	1·83	. .	. .	. .	. .	2·85

Explanation of and remarks on Table VI.

A few words are necessary on the methods of calculating the numbers given in columns five and seven.

If e be the coefficient of longitudinal elasticity, and σ the ratio of lateral contraction to elongation, it can easily be proved that if we subject a wire to a fluid pressure of 1 grm. per square centimetre, the decrease in length per unit thereby produced will be $\frac{1-2\sigma}{e}$. If then A denote the decrease per unit of resistance produced by the pressure, it follows that the decrease attending pressure which would suffice to halve the length of the wire would be $A \div \frac{1-2\sigma}{e}$, and in this way the numbers in column five have been determined from those in column two; the values of e and σ being those given in Part I., with the exception of the value of σ for brass, which has been taken from MALLOCK's paper,* as I have reason to believe that the values of σ obtained by me for this metal are too large. Again, since the pressure would for such small amounts as are used here cause a decrease of section which would be double the decrease of length, the effect of the pressure in merely altering the dimensions would be to increase the resistance by 1 per unit. In order, therefore, to deduce the values in column seven from those in column five we have only to increase the former by 1.

It will be noticed that the *total* alteration of resistance produced by the fluid pressure is in all cases less than the alteration produced by the same amount of longitudinal stress, the ratio of the latter alteration being to that of the former as 1·83 : 1; but that the alteration of resistance when *the same change of length* is produced by the two kinds of stress is, except in the case of lead, greater when fluid pressure is

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* Proc. Royal Society, June, 1879.

employed than with longitudinal stress, and that the alteration of *specific resistance* is much greater for the former kind of stress than for the latter, the ratio being about 2·85 : 1.

The small alterations of resistance which can be produced by fluid pressure as shown in this table prove also how impossible it would have been to detect with such changes of pressure as can be effected by an air-pump any alteration of resistance due directly to compression, and therefore the value of the mode of experimenting already alluded to in determining the amount of lowering of the temperature of the freezing-point of water by pressure : in fact, the change of resistance due to the lowering of the temperature of the melting-point of ice by the pressure would be more than 22 times the change of resistance due to the pressure only.

A brief consideration also suffices to show that the alteration of resistance due to any change of temperature is in all cases very much greater than that which would follow from the same change of volume produced by mechanical stress; this will be seen at once from a glance at the next table.

TABLE VII.

Name of metal.	Coefficient of cubical expansion at 20° C.	Increase of resistance per unit caused by a rise of 1° C. at 20° C.	Rise of temperature necessary to double the volume =A.	Increase of resistance per unit caused by rise of temperature A = B.	Increase of resistance per unit if the wire could have its volume doubled by mechanical stress =C.	Ratio of B : C.
			° C.			
Lead . .	·8223 × 10⁻⁴	·00375	12,160	45·6	0·962	47·4
Copper .	·4554 × 10⁻⁴	·00380	21,960	83·5	0·904	92·4
Iron . .	·3420 × 10⁻⁴	·00470	29,250	137·5	1·393	98·7
Brass . .	·5450 × 10⁻⁴	·00122	18,350	22·4	0·746	30·3

We see from this last table that the alteration of resistance due to any change of temperature is in the case of the four metals, lead, copper, iron, and brass, from 30 to nearly 100 times as great as that which would follow from the same change of volume produced by mechanical agency; and it would appear, again, therefore, that the increase of resistance caused by rise of temperature is principally due to other causes than mere expansion.

PERMANENT ALTERATION OF RESISTANCE PRODUCED BY LONGITUDINAL TRACTION.

Limit of elasticity.

Experiments on the permanent alteration of resistance produced by traction possess considerable advantages in determining the limit of elasticity over the methods usually adopted. In the first place, it is possible to detect much more minute elongations, even though very small lengths of the wire be employed, than would be the case if 100 feet of the wire could be tested in the ordinary way with the cathetometer, and in the second, all errors arising from the wires not being perfectly straight at the commencement of the experiments are entirely avoided.

The limit of elasticity raised by previous loading.

ROBERT THALÈN* with, no doubt, others has shown that in the cases of iron and steel the limit of elasticity can be raised by previous loading.

This was found to be so for all the metals examined, and the next experiment furnishes a fair example of the kind.

Experiment XXI.

An annealed copper wire was very carefully loaded and unloaded by allowing water to flow slowly into and out of a pail attached to it, and the permanent increase of resistance determined after each unloading. The water entered the pail from a vessel containing 5814 grms. of the liquid, and this quantity took five minutes to pass into or out of the pail.

Number of trial.	Number of measures each =5814 grms.	Number of divisions through which it was necessary to move the sliding-piece in order to restore the balance after each unloading.
1	1	14
2	1	1
3	2	31
4	1	0
5	2	2
6	3	54
7	1	0
8	2	2
9	3	9
10	4	80
11	1	0
12	2	0
13	3	0
14	4	7
15	5	122
16	1	0
17	2	0
18	3	0
19	4	0
20	5	25
21	6	235
22	1	0
23	2	0
24	3	0
25	4	0
26	5	8
27	6	29
28	7	1084

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* Pogg. Ann., April, 1865, and Phil. Mag., December, 1865.

Critical points.

THALÈN has also proved[*] that if a curve be drawn having for its ordinates and corresponding abscissæ lines proportional respectively to the permanent extensions and the load producing them, there is a point of maximum curvature, where the increase of length becomes suddenly large compared with the load, and suggests this point, which appears to be nearly at the same part of the curve for different specimens of iron and steel, as a suitable substitute for the so-called "limit of elasticity."

My own investigations have shown that there exist in every metal *two* such points, which I have called critical points, and these are evidently very closely related to the moduli of elasticity. The first of these critical points is one that must of necessity have escaped the notice of most observers of the elongation of wires in the usual manner, as the load required to straighten the wire sufficiently for observations made in this way is beyond this point. Now in the present investigations it is not requisite to straighten the wire, and as the increase of resistance proves to be almost exactly proportional to the permanent elongation, it is evident that the curves showing the relations between permanent extension and load will be similar to those connecting permanent increase of resistance and load.

Experiment XXI. furnishes a good example of the first critical point. It will be seen that the first critical point occurs at the seventh measure, this producing a permanent increase of resistance the ratio of which to that produced by the previous measure is appreciably greater than any of the other similar ratios.

The following experiment is a sample of a series undertaken with a view to ascertain the position of the two critical points for the different metals.

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[*] Phil. Mag., December, 1865.

Experiment XXII.

A well-annealed silver wire was suspended for trial with the scale-pan attached, and loads increasing by 1 kilog. at a time were put on for three minutes and then removed, when the permanent increase of resistance was determined for each load.

Load in kilogs.	Increase of resistance in divisions of platinum-silver wire.
1st	40
2nd	40
3rd	45
4th	60
5th	75
6th	80
First critical point . 7th	142
8th	186
9th	306
Second critical point 10th	1436
11th	2706

Each division of the platinum-silver represents in this case an increase of resistance of only $\frac{1}{1240}$ per cent., and as the percentage of permanent elongation is half of this fraction, because the wire is decreased in section very nearly in the same proportion as it is increased in length, it follows that the total elongation produced by all the loads up to the first critical point inclusive, does not exceed ·2 per cent.

The case of iron.

The behaviour of iron under longitudinal traction is very remarkable; this metal, if the load be applied in small quantities at a time, is seen at certain points to become perfectly rigid, so that the further application of stress does not produce any further permanent elongation until the load has reached a certain value, when elongation once more commences.* Further, iron possesses three critical points at least, and may be found to have more;† these points are well shown in Experiment XXIII.

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* This was first noticed by J. T. BOTTOMLEY (Proc. Roy. Soc., No. 197, 1879), who kindly lent me some of the same kind of wire as that used by himself.

† Perhaps other metals may have more than two critical points, which might be discovered by loading the wires more gradually.

Experiment XXIII.

ANNEALED iron wire.

Load in kilogs.		Permanent increase of resistance represented by divisions of platinum-silver wire.
	1st	5
	2nd	8
	3rd	17
	4th	21
	5th	29
	6th	33
	7th	42
First critical point	8th	120
	8½	118
	9th	40
	9½	25
	10th	30
	10½	35
	11th	0
	11½	15
	12th	83
	12½	177
	13th	223
	13½	389
Second critical point	14th	2356
	14½	2028
	15th	1421
	15½	2052
	16th	36
	16½	24
	17th	304
Third critical point	17½	1603
	18th	Broke

It will be seen from the above experiment that there is a critical point at the 8th kilog., another at the 14th kilog., and a third at the 17th kilog.

The two critical points were determined in all cases by finding the two points where the ratio of the increases of resistance produced by consecutive equal loads is greatest; the next experiment furnishes an example of the method adopted.

Experiment XXIV.

ANNEALED German-silver (2).

Load in kilogs.	Increase of resistance in divisions of the platinum-iridium wire.	Ratio of consecutive increases of resistance.
1st 2	21	
2nd 2	51	2·43[*]
3rd 2	59	1·15
4th 2	65	1·10
5th 2	90	1·38 1st critical point.
6th 2	117	1·30
7th 2	143	1·22
8th 2	326	2·28
9th 2	1083	3·32 2nd critical point.
10th 2	1156	1·07

The weight of the scale-pan, pulley, &c., was 2·5 kilogs., or 1·25 kilogs. on each part of the wire, therefore the total load at the first critical point is equal to 11·25 kilogs., and that at the second 19·25 kilogs. Now the section of the wire at the two points is ·00883 and ·00876 per square centimetre; hence the load at the first critical point is 1274 and at the second 2197 kilogs. per square centimetre.

In Table VIII. will be found the loads at the two critical points and their relation to "YOUNG's modulus."

TABLE VIII.

Name of metal.	Value of e in grms. per square centim.	Load at the first critical point in grms. per square centim. $=\alpha$.	Load at the second critical point in grms. per square centim. $=\beta$.	Ratio $e:\alpha$.	Ratio $e:\beta$.
Iron (1)	1981×10^{6}	$2·070\times10^{6}$	$3·009\times10^{6}$	$9·6\times10^{2}$	$6·6\times10^{2}$
Nickel (1)	2175 „	2·200 „	3·100 „	9·9 „	7·0 „
Platinum (1)	1490 „	1·400 „	1·520 „	10·6 „	9·8 „
German-silver (2). . . .	1291 „	1·274 „	2·197 „	10·1 „	6·0 „
Copper (2)	1218 „	1·151 „	. .	10·7 „	. .
Copper (1)	1160 „	1·115 „	1·702 „	10·4 „	6·8 „
Copper (3)	1143 „	1·230 „	1·870 „	9·3 „	6·1 „
Platinum-silver (1) . . .	1051 „	1·081 „	1·741 „	9·8 „	6·0 „
Silver (1)	742 „	·819 „	1·250 „	9·1 „	6·0 „
Aluminium (1).	673 „	·730 „	1·120 „	9·2 „	6·0 „
Mean for all the different metals	. .	. .	. .	$9·8\times10^{2}$	$6·7\times10^{2}$

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[*] In this, as in several other experiments, the first of the ratios of consecutive increases is greater than several of those which follow, but this is probably due to the fact that the weight of the scale-pan had been acting on the wire for some hours previous to the period of actual testing.

Remarks on Table VIII.

It is evident from the last table that the loads both at the first and second critical points, in the case of each substance, bear a constant ratio to the corresponding value of "YOUNG's modulus," there being quite as much difference between the several ratios $\frac{e}{\alpha}$ and $\frac{e}{\beta}$ for the three specimens of copper as for the various metals. The time during which the load was allowed to act was in all cases the same, namely, three minutes,* and the wire was relieved of all weight except that of the scale-pan before determining its alteration of resistance.

Experiment XXI. having shown that the position of the critical points must be altered by the process of wire-drawing, it is necessary that very great care should be taken in annealing the wire† if we wish to determine the true position of these points for any substance whose particles are to be free from mutual strain previous to beginning the experiments. The theoretically correct definition of the "limit of elasticity" would be the highest load per unit of surface which a wire can bear without undergoing the slightest permanent elongation. It is clear, however, that we cannot, even with the utmost care, obtain a substance which will have its particles in a *perfectly homogeneous* condition, and it will of necessity happen that *some* of the particles are on the point of passing the elastic limit or, at any rate, that some are much nearer this limit than others, before any external stress has been applied. Consequently we can never hope to obtain the true value of the elastic limit by merely endeavouring to observe the first trace of a permanent elongation, our power to do so depending upon the delicacy of our instruments; but we can accomplish our object in all probability by determining the point at which the ratio of the elongation and the stress producing it reaches its first maximum. I would venture, therefore, to suggest, that the *first*‡ of the two so-called critical points be taken to represent the true "limit of elasticity" of a well-annealed substance, and to agree with THALÈN that neither the method of measuring the limit of elasticity by the greatest load which will produce sensible permanent elongation, nor the purely arbitrary one adopted by WERTHEIM and others of fixing an elongation of ·0005 of the unit length as corresponding to this limit, is desirable.

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* Except in the case of copper (3) where five minutes was allowed.

† It is certainly not sufficient to heat a wire to redness *for a few minutes*, and then allow it to cool slowly; the high temperature must be maintained in some cases for a considerable time.

‡ The *second* of the critical points is evidently the same as that suggested by THALÈN as being suitable for measuring the limit of elasticity (Phil. Mag., December, 1865), but I think that the second point is rather the precursor of breakage than of the passage of the elastic limit.

Critical points of tin and lead.

The positions of the critical points of these metals have not been satisfactorily determined though several trials were made for that purpose, and in some of these great care was taken to load by very small amounts at a time and to allow each weight to remain on the wire for a considerable period; in the following experiment each load was left on the wire for 48 hours :—

Experiment XXV.

ANNEALED lead wire.

Load in tenths of a kilog.	Increase of resistance in divisions of the platinum-iridium wire.	Ratio of consecutive increases of resistance.
1st tenth	7·0	. .
2nd	16·5	2·4
3rd	38·0	2·3
4th	49·0	1·3
5th	66·0	1·4
6th	103·0	1·6
7th	207·0	2·0
8th	540·0	2·6
9th	wire broke.	. .

If we regard the second load as the load at the first critical point, and the eighth as the load at the second critical point, we obtain for the loads at the two critical points respectively the values 48 kilogs. per square centimetre* and 74 kilogs. per square centimetre; in this case $\frac{e}{\alpha}$ would $=35\times 10^2$, and $\frac{e}{\beta}=22\cdot 6\times 10^2$, both these numbers being much larger than the values of $\frac{e}{\alpha}$ and $\frac{e}{\beta}$ for the metals in Table VIII.

With tin, also, the loads at the first and second critical points, as far as the latter could be determined,† seemed much less in proportion to the value of e than was the case with most of the other metals.

In Table IX. the permanent increase per cent. of resistance produced by longitudinal traction is shown for each metal by a series of curves; and these curves will also show very fairly the permanent increase per cent. of length produced, since the former is very nearly equal to twice the latter.

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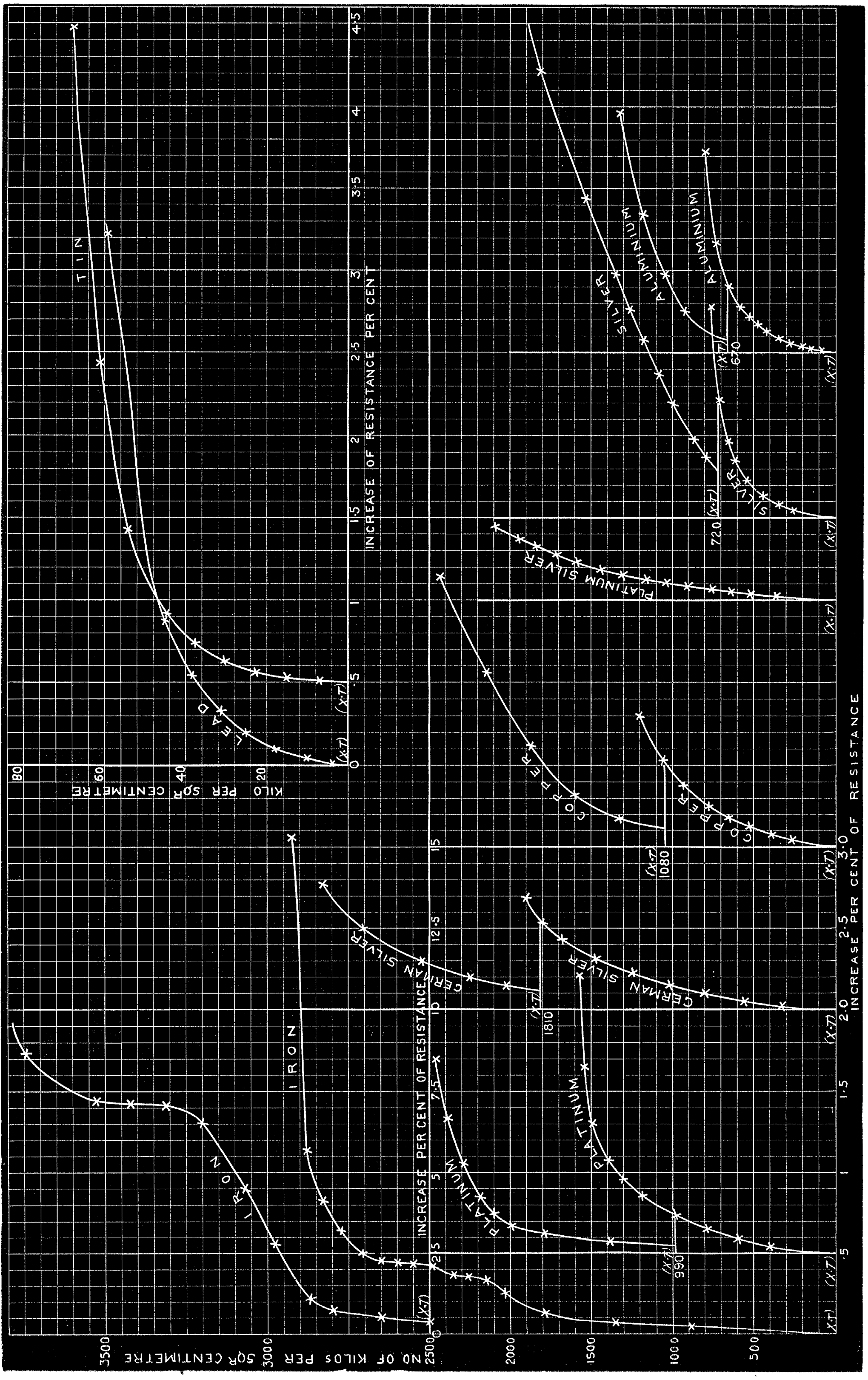
* 30 kilogs. per square centimetre added for the permanent load, consisting of pulley, &c.

† I am inclined, however, to attach very little value to the observations made on the critical points of lead and tin; very probably better results might be obtained by using wires of much greater section than those here employed.

TABLE IX.


TIN
LEAD
IRON
PLATINUM
GERMAN SILVER
COPPER
PLATINUM SILVER
SILVER
ALUMINIUM
(X·T)
1080
1810
990
720
670
INCREASE OF RESISTANCE PER CENT
0
.5
1
1.5
2
2.5
3
3.5
4
4.5
KILO PER SQR CENTIMETRE
80
60
40
20
INCREASE PER CENT OF RESISTANCE
2.5
5
7.5
10
12.5
15
INCREASE PER CENT OF RESISTANCE
.5
1
1.5
2.0
2.5
3.0
NO OF KILOS PER SQR CENTIMETRE
3500
3000
2500
2000
1500
1000
500

Explanation of and remarks on Table IX.

The curves are in most cases divided into two parts, the lower part representing the increase of resistance per cent. up to and a little beyond the first critical point, and the upper one the increase up to and beyond the second critical point. The abscissæ represent the increase of resistance per cent. for the lower curves on a scale of 40 millims. to unit increase per cent., and for the upper ones on a scale of 80 millims. to unit increase per cent.

The ordinates represent the load per square centimetre in kilogrammes, and are on a scale of 40 millims. to each 1000 kilogs. for the lower curves and of 80 millims. to each 1000 kilogs. for the upper ones.

The upper curves start from the horizontal lines drawn through their lower extremities, and the starting points on these lines are set off at distances representing on the scale for the upper curves the increase of resistance already attained: also opposite each horizontal line is placed the number of kilogrammes per square centimetre already put on to the wire. In all cases the origin of coordinates is marked X, T.

Thus, for example, the upper extremity of the lower copper curve has an abscissa $=32$ millims. and an ordinate of 48 millims, therefore the load at this point is $48\times\frac{1000}{40}$ or 2400 kilogs. per square centimetre; and the increase of resistance is $32\times\frac{1}{40}$ or 8 per cent. Similarly the upper extremity of the upper copper curve has an abscissa of 65·6 millims. and an ordinate reckoned from the horizontal line passing through the lower extremity of the curve of 56·8 millims., therefore the total load is $56{\cdot}8\times\frac{1000}{80}+1080$ or 1790 kilogs. per square centimetre, and the increase of resistance $65{\cdot}6\times\frac{1}{8}$ or 8·2 per cent.

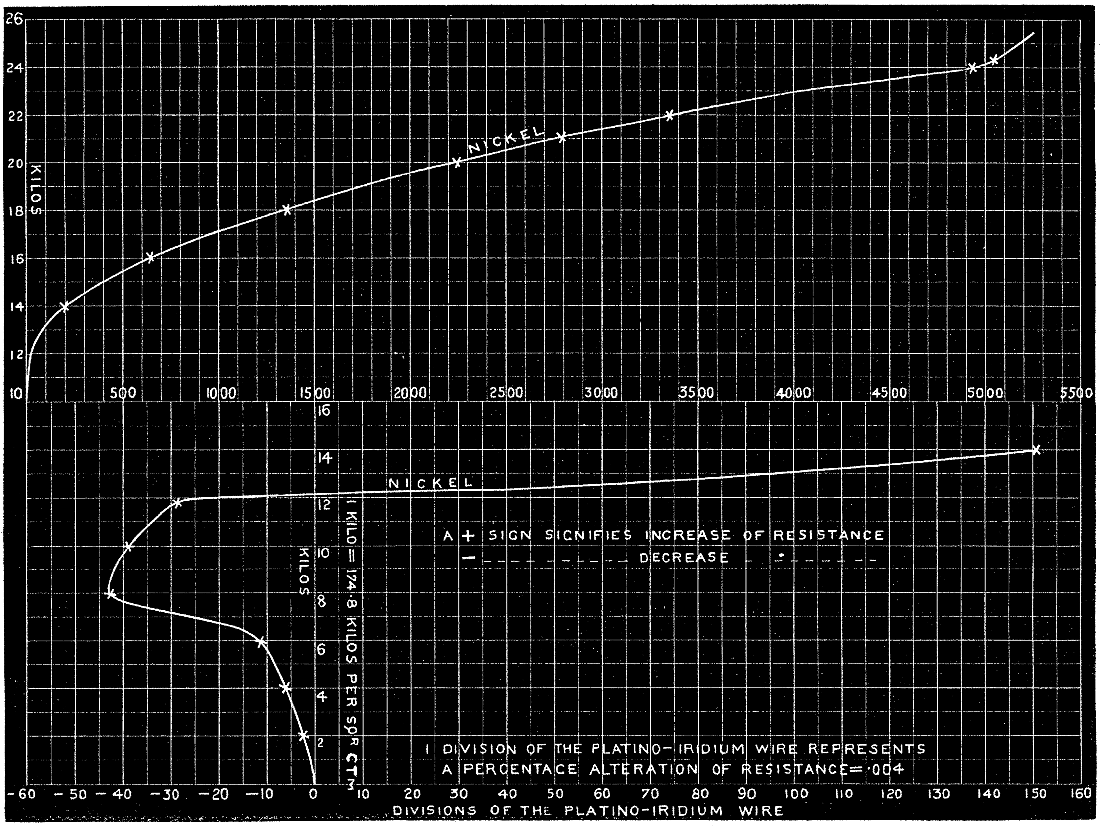
In order to include lead and tin in the same table it was found necessary to reckon the load on a scale of 2 millims. to 1 kilog. per square centimetre, and the increase of resistance on the same scale as that used for the lower curves of the other metals. Moreover, to the load registered in the table there should be added for these metals 30 kilogs. per square centimetre, this representing the permanent load on the wires.

It will be observed that there is in most cases a considerable resemblance between the forms of the upper and lower curves, and that in the case of iron the curve near the two critical points becomes very nearly a vertical straight line.

The critical points of nickel.

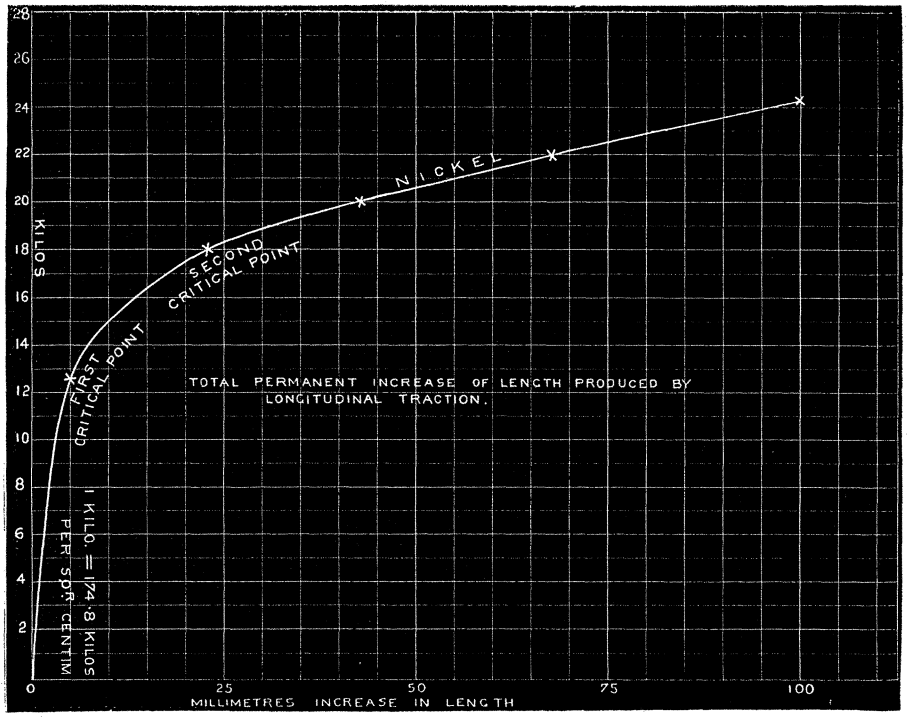
We have seen that the electrical resistance of nickel is altered in a peculiar manner by temporary longitudinal traction, and we might expect, therefore, that the effect of permanent extension would perhaps be different in the case of this metal, both in character and extent, from what it is with other substances. This is found to be so, and Table X. shows that the total permanent alteration of resistance produced by permanent extension is in the first instance of the nature of a decrease, but that, after a certain load has been reached, the resistance begins, as in other metals, to increase. The curves in Table X. are drawn with their abscissæ to represent the alteration of resistance—for the lower one on a scale of 1 division of the platino-iridium wire to the millimetre, and for the upper one on a scale of 25 divisions of the platino-iridium wire to the millimetre.

Table X.—Curve showing the total permanent alteration of electrical resistance produced by longitudinal traction from 10 to 24½ kilogs., and curve showing the permanent total alteration of electrical resistance produced by longitudinal traction from 0 to 14 kilogs.



In both curves the ordinates represent the number of kilogrammes on the wire to a scale of ·2 kilog. to the millimetre. The lower curve which represents the permanent alteration of resistance produced by loads up to 14 kilogs., shows that the resistance decreases to an extent which is nearly proportional to the load up to 6 kilogs.; here a sudden leap is made of rapid decrease of resistance, but on reaching the next load, 8 kilogs., the curve turns, and just at the 12th kilog. there occurs a sudden and rapid increase of resistance. The upper curve which starts from the 10th kilog. shows that the rapid increase begun at the 12th kilog. is continued to an extent which is nearly proportional to the load up to the breaking point of the wire. The nature of these curves would seem to show critical points at the 6th, 8th, and 12th kilogs., but as the effect on the *specific resistance* of this metal was found to be very great in comparison with that of the other substances, it was evident that the critical points as understood to mean points of sudden increase of *length* compared with the load producing it could not safely be deduced from the curve showing the total alteration of resistance. The critical points have therefore been deduced from direct observations of the permanent increase of length produced by each load, and the results of these observations are shown in the curve of Table XI. This curve has its abscissæ representing the permanent increase of length on a scale of ·625 millim. of increase of length to the millimetre and its ordinates the load in kilogrammes on a scale of ·2 kilog. to the millimetre. From the observations of increase of length the first critical point was determined to be at the load 2200 kilogs. per square centimetre and the second at the load 3100 kilogs. per square centimetre.

TABLE XI.—Total permanent increase of length produced by longitudinal traction.



THE INFLUENCE OF TIME ON THE AMOUNT OF PERMANENT INCREASE OF RESISTANCE OR OF LENGTH WHICH CAN BE PRODUCED BY LONGITUDINAL STRESS.

It is well known to all who have made investigations in the subject of elasticity, that the permanent increase of length which can be produced by a given amount of longitudinal stress depends largely upon the time during which the stress is allowed to act, and as it was expected that experiments on the permanent increase of resistance would throw some light on this influence of time, several trials were made with a view of ascertaining whether a wire will, when under the action of considerable stress, show greater and greater increase of length until it breaks, or whether the time-curve of its increase of length will be asymptotic.

Experiment XXVI.

A piece of copper (3) having been loaded for some time with six measures of water was still further loaded with one measure, this being allowed to enter very slowly into the pail attached to the wire; the current from a DANIELL'S element was kept flowing through the "bridge" circuit, and the alteration of resistance observed by noting the position of the light on the scale.

Time in minutes after the completion of the loading.	Increase of resistance* for each minute in terms of the deflection of the light in scaled divisions.	Difference of increase for consecutive minutes.
1	45	. .
2	31	14
3	25	6
4	24	1
5	18	6
6	16	2
7	16	0
8	15	1
9	17	−2
10	10	7
11	13	−3
12	14	−1
13	13	1
14	7	6
15	5	2
16	8	−3
17	10	−2
18	8	2
19	5	3
20	7	−2

From the last experiment we learn that, though the wire had been so carefully loaded and the room free from vibrations of any sort, the increase of resistance did not, *shortly after loading*, take place smoothly, but the difference of increase of resistance for consecutive minutes became alternately greater and less.

In the next experiment the increase of resistance is measured by the number of divisions of the platino-iridium wire through which it was necessary to move the sliding-piece in order to restore the balance, and the times recorded are those taken to produce the increase of resistance.

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* Each scale-division here represents an alteration of resistance equal to about ten-millionths of the whole.

Experiment XXVII.

The same wire as in the last experiment was allowed to run down for a few minutes longer, and then the following observations were made :—

Increase of resistance in divisions of the platino-iridium wire.	Time in minutes.	Ratios of consecutive times.
1st . . 40	13·0	. .
2nd . . 40	19·0	1·462
3rd . . 40	24·0	1·262
4th . . 40	30·0	1·250
5th . . 40	41·8	1·394
. . . . .	. . . .	. . . . .
. . . . .	. . . .	. . . . .
11th . . 83·40	415	. .
Mean value of ratios = 1·342.		

It is to be noticed that here the increase of resistance takes place more regularly; and though the ratios of consecutive times are not very constant, it would seem that the times form a geometrical progression, since the time for the last increase of resistance, as calculated from the formula $t=13\times 1{\cdot}342^{11{\cdot}83}$, where t denotes the time, is 422 minutes—a number agreeing sufficiently well with the observed time.

The wire was afterwards loaded more and more, and the values of the ratios of consecutive times, as determined in the same manner as in the last experiment, are recorded in Table XII.

TABLE XII.

Resistance of the wire in terms of the comparison-wire.	Total load on the wire in measures of water, each measure = 5·825 kilogs.	Calculated load in kilogs. per square centim.	Percentage value of the increments of resistances represented by 40 divisions of the platino-iridium wire.	Ratios of the consecutive times required by the loads to produce equal increments of resistance.											Mean values of ratios.	Mean values of ratios calculated for a percentage increment of resistance = ·1.
1·056	9 10	1448	·0314	1·24	2·00	1·21	1·33	1·29	1·17	1·33	1·50	1·27	1·24	1·22	1·35	2·572
1·080	9·75	1570	·0311	1·33	1·38	1·32	1·35	1·08	1·21	1·18	1·30	1·20	1·24	..	1·26	2·097
1·120	10·75	1759	·0305	1·10	1·21	1·07	1·23	1·14	1·17	1·14	1·25	1·18	1·13	1·25	1·17	1·721
1·177	11·75	1971	·0298	1·12	1·15	1·13	1·16	1·08	1·12	..	..	..	..	..	1·13	1·492

We learn from Table XII. that the ratios of consecutive times become more and more constant as the load on the wire is made larger and larger, and therefore that the velocities of increase of resistance for small equal increments of resistance form a geometrical progression.

In order to make the mean values of the common ratios comparable with each other, the common ratios calculated for equal increments of resistance of ·1 per cent. are recorded in the last column; the calculation was effected by raising the observed ratio in the last column but one to the power obtained by dividing ·1 by the percentage values of the equal increments of resistance given in the fourth column. For example, with a load of 1448 kilogs. per square centimetre, the common ratio of the geometrical progression found by the times taken for the load to increase the resistance by successive percentage amounts of ·0314 was found to be 1·35, therefore the ratio which would have ensued, if the times taken to increase through ·1 per cent. had been observed, would have been $1{\cdot}35^{\frac{\cdot 1}{\cdot 0314}}$ or 2·572.

Again, the loads in kilogrammes per square centimetre given in the third column are calculated from the resistances given in the first column in the following manner: let S_1 and S_2 be the sections of the wire before and after stretching, and let the corresponding resistances be R_1, R_2, and the lengths l_1 and l_2; then, $\frac{R_2}{R_1}=\frac{l_2}{l_1}\times\frac{S_1}{S_2}$, provided that there be no change in the specific resistance of the metal; also $l_1\times S_1=l_2\times S_2$, or $\frac{l_2}{l_1}=\frac{S_1}{S_2}$, provided that the stretching does not alter the density. But we shall see that neither the density nor the specific resistance is altered by stretching to any extent sufficient to introduce any appreciable error, therefore we have within a sufficiently close approximation $\frac{R_2}{R_1}=\left(\frac{S_1}{S_2}\right)^2$, or $S_2=S_1\times\sqrt{\frac{R_1}{R_2}}$. Thus the section S_1 having been determined, it is easy to ascertain the section after any amount of stretching. For example, the section of the wire last used was before stretching ·0183 square centim., and the resistances before and after the stretching were 1·056 and 1·080 respectively, therefore the section of the wire after stretching would be nearly $\cdot 0183\times\sqrt{\frac{1\cdot 056}{1\cdot 080}}$, and the actual load on the wire being 9·75 measures of water or $9{\cdot}75\times 5{\cdot}825$ kilogs., the load per square centimetre would be $\frac{9\cdot 75\times 5\cdot 825}{\cdot 0183}\times\sqrt{\frac{1\cdot 080}{1\cdot 056}}$ kilogs. $=1570$ kilogs. In all cases the resistances recorded in the first column are the means between the resistances observed at the commencement and end of the times during which the velocities of increase were noted, and the wire was allowed to run down for some time (about 20 minutes) before the observations of the velocities of increase commenced.

It is, moreover, evident from the last column in the table that the common ratio of the geometrical progression becomes less and less as the load becomes larger and larger, and we might expect to find some relation between the decrease of velocity of increase of resistance and the difference between the breaking-load and the load actually on the wire. A further examination of the results given in Table XII. shows that a relation does exist of an extremely simple nature; in fact, if we denote the breaking-load and the actual load on the wire by P and p respectively, the decrease per unit of the velocity of increase of resistance is inversely proportional to $P-p$. The value of P was carefully determined by loading pieces of the wire by moderate amounts at a time, and allowing each load to remain on the wire some ten minutes before each further addition, and measuring the diameter *close to the point of breakage* by means of a wire-gauge graduated to ·01 millim. The mean of several trials gave a value for P of 2625 kilogs. per square centimetre.

Now if t_1, t_2, t_3, &c., are the times taken to increase the resistance by successive equal and small amounts, the ratios $t_2 : t_1$, $t_3 : t_2$, &c., have been proved to be constant for the same value of p: let this constant be denoted by r; then the decrease per unit of the velocity of increase of resistance being $=\frac{1}{t_1}-\frac{1}{t_2}\div\frac{1}{t_1}$ will therefore $=\frac{r-1}{r}$, and accordingly if the above-mentioned relation holds good, $\frac{r-1}{r}\div(P-p)$ should be a constant for different values of p. The last column of the table gives the values of r for the loads given in the third column, and the values of $\frac{r-1}{r}\div(P-p)$ are for the four loads there recorded, ·000519, ·000496, ·000484, and ·000504, with a mean value of ·000501.

The question next arises, will the ratio $\frac{r-1}{r\times(P-p)}$ be the same for other metals as for copper? for if so we can calculate the breaking-load by merely loading the wire beyond the second critical point and observing the value of r; then, since $\frac{r-1}{r\times(P-p)}=\cdot 000501$,

$$P=p+\frac{r-1}{r\times\cdot 000501}.$$

With a view of ascertaining whether the breaking-load could be thus calculated, a series of experiments with different metals was begun, the mode of operating being similar to that just described in the case of copper, and the results are shown in the next table. In the same table are also given the ratios of the different moduli of longitudinal elasticity to the corresponding breaking-load.

TABLE XIII.

Metal.	Percentage value of the equal increments of resistance.	Actual load on the wire in kilogs. per square centim. $=p$.	Ratio of consecutive time calculated for an increase of ·1 per cent. of resistance $=r$.	Calculated breaking-load $P=p+\frac{r-1}{r\times\cdot000501}$.	Observed breaking-load in kilogs. per square centim.	Mean values of breaking-loads from observation and calculation.	Ratio of "YOUNG'S modulus" to breaking-load.
Copper (3) . .	·0314	1448	2·572	2666	2625	2625	$4\cdot35\times10^2$
	·0311	1570	2·097	2612	. .		
	·0305	1759	1·721	2593	. .		
	·0298	1971	1·492	2628	. .		
Iron (1) . . .	·2270	3311	1·081	3826	3816	3825	5·17 „
	. .	. .	. .	. .	3785		
	. .	. .	. .	. .	3867		
Zinc (2) . . .	·9620	1418	1·014	1446	1468	1460	5·25 „
	. .	. .	. .	. .	1528		
	. .	. .	. .	. .	1426		
Platinum (1) .	·1524	1737	1·131	1968	2061	2021	7·20 „
	·1487	1836	1·064	1956	2080		
	·1482	1946	1·029	2004	2099		
Silver (1) . .	·0609	1076	2·531	2281	2090	2185	3·44 „
	·0601	1192	2·015	2195	2272		
	·0582	1440	1·498	2099	2170		
Aluminium (1)	·0552	864	1·144	1295	1277	1293	5·19 „
	. .	. .	. .	. .	1304		
	. .	. .	. .	. .	1288		
							Mean $5\cdot10\times10^2$

Observations on Table XIII.

We learn from the above table how very closely in all cases the calculated breaking-load agrees with the observed breaking-load, though the values of p and of the percentages of increase of resistance for which the times were observed varied considerably. What differences do exist are no greater than those between the values of the observed breaking load for different pieces of the same wire.

Since, also, the permanent increase of resistance produced when a wire is running down under the influence of a load is for small amounts nearly double the increase of length, we may determine the breaking load by observing the times taken by the load to produce successive equal increments of length amounting to ·05 per cent., and use the same formula as above.*

In estimating the breaking-load as has been before mentioned, the diameter of the wire was gauged in the immediate neighbourhood of the breaking-point; and this is necessary if we wish to determine the true breaking-load in kilogrammes per square centimetre, inasmuch as, however uniform in diameter, and however carefully annealed

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* It should be noticed that the value of r as used in the formula is greater than unity, and is obtained by dividing *the succeeding by the preceding time* of accomplishing any two consecutive increments of resistance or of length.

the wire may have been before stretching, the latter action is sure to diminish the diameter at some parts of the wire more than at others, and eventually the wire breaks at that part at which the greatest contraction has taken place.

If a wire could be obtained of perfect uniformity of diameter and substance, the contraction would gradually increase from each end to the centre where it would be greatest, and at this point the wire would break. It is interesting to watch this gradual increase of contraction from the two ends to the middle in the case of a test-bar of ductile iron or steel, and through the kindness of Sir JOSEPH WHITWORTH I was able to make the following experiment on such a bar of fluid-pressed steel, the specimen having been selected as suitable for this purpose in consequence of its great ductility.

The bar had a total length of 6 inches before stretching, but a screw was formed, 2 inches in length (see fig. 16), at each end for the purpose of securing the bar in the framework of the hydraulic press employed to stretch it. The diameter of the bar between the two screws was before testing ·7979 inch, and after each stretching the bar was removed from the press and the length and diameter re-determined: the results obtained are recorded in the next table.

Fig. 16.

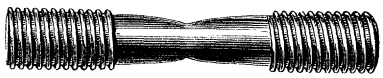

TABLE XIV.

Stress in tons per square inch.	Total permanent increase of length measured after the removal of the stress.	Total permanent contraction of diameter at the centre.	Ratio of permanent contraction of diameter to permanent elongation.
20	·1060	·025	·236
22	·1560	·030	·192
24	·2380	·050	·211
25	·3010	·053	·176
26	·5175	·098	·190
26 Second time	·7850	·228	·294
23½ Broke	·8900	·323	·363

It will be noticed that the ratio of permanent contraction of diameter to the permanent elongation is as sensibly constant as could have been expected from the way in which the diameter had to be measured, namely, by calipers,* until the

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* WHITWORTH'S measuring-machine would have been employed for this purpose as it was for measuring the increase of length, had not the curving of the bar produced by the stretching rendered such an instrument unsuitable.

breaking-load is nearly reached, when the contraction begins very suddenly to increase.

Fig. 16 is from a photograph of a similar specimen, broken after stretching, and shows the gradual contraction from the ends to the centre and the sudden increase of contraction at this point. In measuring the diameter of the broken wires the gauge was placed close to the place of this sudden contraction.

It appears also from Table XIII. that there is a certain amount of relationship between the breaking-load and the modulus of longitudinal elasticity; platinum, however, having too small a breaking-load and silver too high in comparison with the modulus of elasticity when contrasted with the other metals.

It should be remembered that in the case of the former metal the loads at the critical points were less in proportion to the elasticity than was the case with the other metals, and if we regard the breaking-point as a third critical point, it would appear that these three critical points are in the case of well annealed wires related to each other roughly in the ratios of $1 : 1\frac{1}{2} : 2$ or of $2 : 3 : 4$.

THE PERMANENT ALTERATION OF SPECIFIC RESISTANCE CAUSED BY STRESS.

Traction.

We have seen that the alteration of specific resistance which can be temporarily produced by longitudinal traction is very small, but then the temporary lengthening is small also. Now we can with wires which have been well annealed produce, in most cases, a far more considerable permanent increase of length, and it seemed desirable to ascertain whether there would be a correspondingly large change in the specific resistance of the substance.

Three different modes of experimenting were tried :—in the first, the wire to be tested and the comparison-wire were clamped into the blocks already described, and were then stretched at full length on the floor and side by side ; the short block, into which one end of the wire to be stretched was clamped, was placed behind two stout screws, which were screwed into the floor to about one half of their length, and about one inch apart; the wire passed between these screws, and the other end of it which was clamped into the longer brass block was pulled by hand until it was quite straight· a mark on the block which traversed a wooden scale divided into millimetres, and secured to the floor by screws in a position parallel to the length of the wire, serving to measure the length of the wire. It was ascertained that after a little practice the readings could be depended upon to within at least 1 millim. or about $\frac{1}{2400}$ of the whole length. After thus measuring the length, the wires were placed in the air-chamber already described, and after the usual precautions, the ratio of their resistances tested; a weight was now placed on the pulley for three minutes and then removed, when the wire was permitted to remain free from stress for 10 minutes, after which time a new determination of the ratio of the resistances of the wires was made.

The wires were now removed from the air-chamber and the one which had been stretched was remeasured. The same processes were repeated after greater and greater loads until finally the wire was broken. With some of the wires the specific gravity was determined after each stretching, but as the alteration of density was found to be very small with most of the substances, the specific gravity was determined before the stretching had commenced, and again after the wire had been considerably elongated; the density for intermediate amounts of stretching was calculated on the assumption that the change of density is proportional to the increase of length.

In the second method the wires were kept during the whole period of observation in the air-chamber; the hook on the pulley was connected by a fine copper wire, with a brass sliding piece provided with an index and capable of free vertical motion up and down a wooden scale. The lower extremity of the sliding piece was slightly weighted, so as to keep the fine copper wire, which had been previously stretched very nearly to breaking, perfectly straight. The hook on the pulley was also connected by a chain with a lever which served to elongate the wire. On commencing the experiments the weight of the lever was removed from the wire and the resistance of the latter was determined; the position of the index was then noted and afterwards the lever was used to produce the required extension, when again the wire was relieved from stress and after a few minutes the resistance and length of the wire were redetermined. In this way an alteration of length not exceeding $\frac{1}{5000}$th of the whole could be readily measured, but as it was ascertained that in the case of certain wires it was necessary *to remove entirely even the slightest constraint*, such for instance as would be caused by the small weight of the pulley or of the sliding piece, before they would attain in a sufficiently short time their ultimate resistance, a third method was adopted as follows:—

The length of the wire to be examined having been measured as in the first method, it was placed, together with the comparison-wire, at full length in a long wooden box made for the purpose, the two wires having previously been wrapped as usual in paper or surrounded by caoutchouc tubing, and after a sufficient time had elapsed, usually about 15 minutes, to enable them to assume their ultimate ratio of resistance, this latter was determined. The wires were then removed from the box, and the one to be tested stretched as in the first method to a certain extent; they were then replaced, and after the proper time their resistance ratio redetermined. At each removal of the wires from the box the connexions with the other parts of the bridge had to be disturbed; but it was ascertained, as indeed might have been expected from the mode of experimenting,* that this did not in the least affect the value of the ratio of the resistances of the two wires. A few examples will suffice to show the nature of the results obtained.

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* I have frequently removed and replaced the connexions of the wires without causing any alteration of resistance which would amount to $\frac{1}{20000}$th of the whole.

Experiment XXVIII.

A wire of annealed silver, 8 feet in length and ·085 centim. in diameter, stretched by loading.

Load in kilogs.	Total increase of length per cent. produced by the load = A.	Total increase of specific resistance per cent. produced by the load = B.	Ratio of B : A.
5	1·15	. .	. .
6	3·64	+·034	·0094
6¾	7·28	+·274	·0376
7¼	9·38	+·246	·0262

Experiment XXIX.

A wire of annealed copper, 8 feet in length and ·095 centim. in diameter, stretched by hand.

Total increase of length per cent. produced by stretching = A.	Total increase of specific resistance per cent. produced by stretching = B.	Ratio of B : A.
2·42	+0·395	·163
4·84	+0·649	·134
11·33	+0·373	·030
23·36	+0·296	·013

Experiment XXX.

A wire of annealed iron, 8 feet in length and ·092 centim. in diameter, stretched by means of a lever, *the stress produced by the weight of the lever being allowed to remain after the permanent extension had been completed.*

Total increase of length per cent. produced by stretching = A.	Total increase of specific resistance per cent. produced by stretching = B.	Ratio of B : A.
3·75	+·129	·034
7·96	·224	·028
11·85	·384	·032
15·74	·640	·041

Experiment XXXI.

A wire of annealed iron, 8 feet in length and ·092 centim. in diameter, stretched by hand.

Total increase of length per cent. produced by stretching = A.	Total increase of specific resistance per cent. produced by stretching = B.	Ratio of B : A.
5·74	−·105	−·0183
7·51	−·143	−·0190
9·49	−·156	−·0164
11·56	−·177	−·0153
16·36	−·150	−·0091

Experiment XXXII.

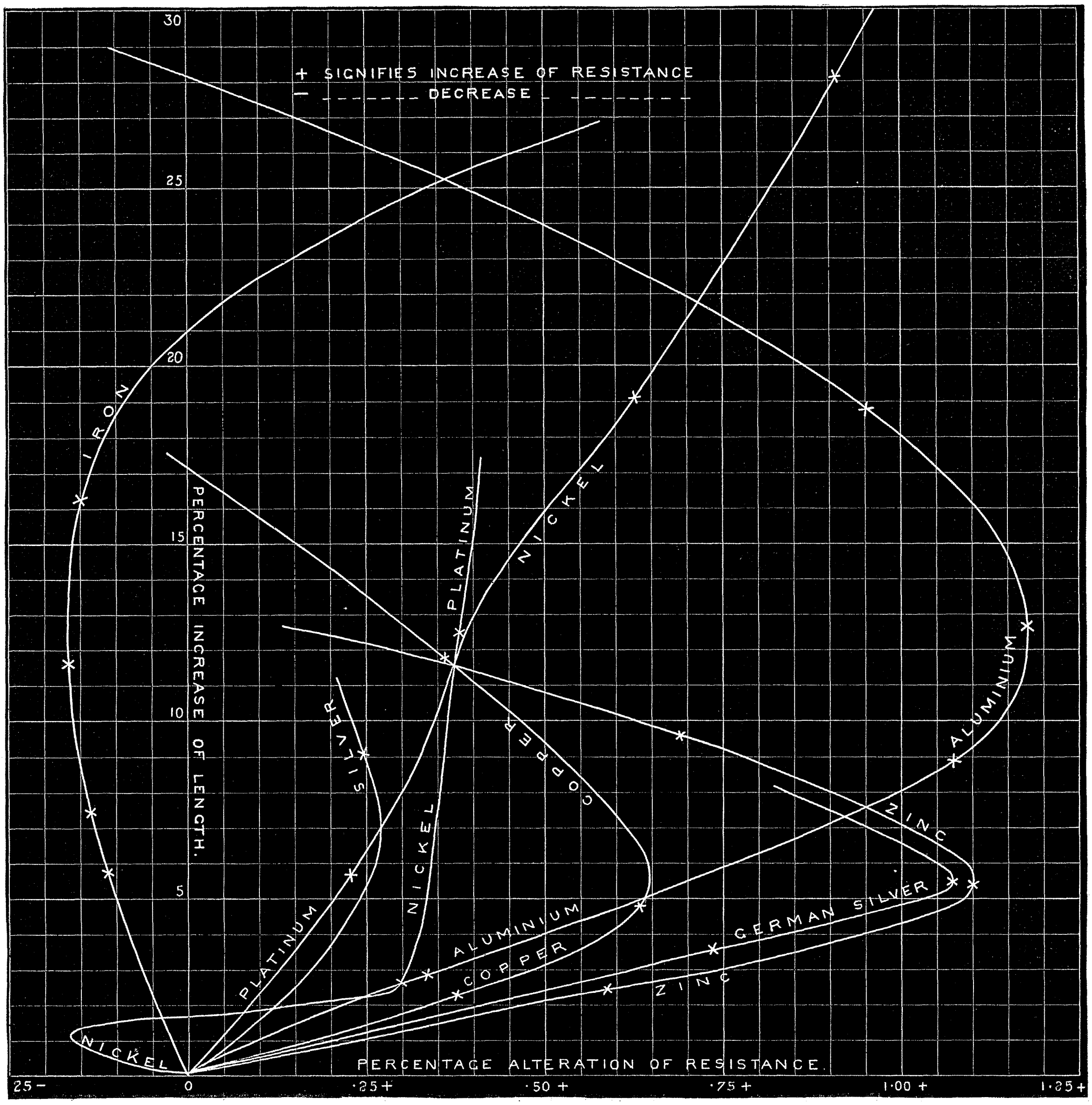
A wire of annealed nickel, 8 feet in length and ·106 centim. in diameter, stretched by loading.

Load in kilogs.	Total increase of length per cent. produced by the load = A.	Total increase of specific resistance per cent. produced by the load = B.	Ratio of B : A.
12	0·32	−0·757	−2·366
18	1·67	+1·260	0·755
20	3·06	+1·514	0·494
22	4·82	+2·052	0·426
24½	7·14	+3·634	0·509

It will be observed that of the four metals—silver, copper, iron and nickel—the two former are at first increased in specific resistance, and that the increase only continues up to a certain amount of stretching when, having reached a maximum, it begins to decrease; whilst with the two latter the first alteration of resistance is in the way of a decrease, which also after attaining a maximum begins to diminish, and with nickel there is soon a comparatively large increase. Of nine metals which have been examined, iron and nickel are the only two which in the first instance show a decrease of specific resistance, whilst the remaining seven are similar to copper and silver in respect to the change of specific resistance due to permanent extension. In the following table the effects of different amounts of permanent longitudinal extension on the specific resistance of copper, zinc, German-silver, nickel, platinum, iron, aluminium and silver are shown by a series of curves. The abscissæ of these curves represent the percentage alteration of specific resistance, and the ordinates the percentage alteration of length, the former on a scale of ·0125 percentage alteration to the millimetre, and the latter on a scale of ·25 percentage alteration to the millimetre;

with nickel, however, the alteration of resistance is so very much larger in proportion to increase of length than is the case with the other metals, that the abscissæ are represented on a scale of ·05 percentage of alteration to the millimetre, and the ordinates on a scale of ·0625 percentage alteration to the millimetre.

TABLE XV.—Curves showing the permanent alteration of specific resistance produced by permanent longitudinal extension.



Remarks on Table XV. and Experiments XXVIII. to XXXII. inclusive.

It should be stated that before making any observation of the resistance or length, the wire was stretched about 2 per cent. of the original length in order to render it sufficiently straight, and that the resistance and length after this stretching are taken as the starting points from which the percentage alterations are measured; in the cases, however, of German-silver and nickel this was not done, as they were deemed to be sufficiently straight without stretching, and, moreover, not capable of much extension before breaking.

The curves are evidently of parabolic shape, except perhaps in the case of nickel, whose behaviour seems to be quite abnormal. With this metal the curve after passing to the left, showing that the specific resistance is diminished by extension, takes a sharp turn round to the right, and, after passing almost vertically upwards, makes another bend afterwards, proceeding almost in a straight line. Experiment XXXII., as well as the curve for nickel also, show how much larger is the alteration of specific resistance, whether decreasing or increasing, in comparison to the alteration of length, than is the case with any of the other metals.

By comparing Experiment XXX. with Experiment XXXI., we see the effect of leaving a load on the wire after the extension has taken place; the decrease of specific resistance of iron produced by a moderate amount of extension is in this case replaced by an increase. Now we have seen in Part I. that the wire will not quite assume the length which it would have if entirely relieved from stress, but the change in resistance is much larger than can be accounted for by any change of dimensions, and in some instances the effect of a much slighter restraint than was produced by the stress of the lever sufficed to make a very appreciable difference in the specific resistance. The silver wire formed a remarkable example of the kind; with this wire the specific gravity was determined after each stretching, and the resistance was measured both before and after the former operation, the only load left on the wire being that of the pulley, which produced a stress of a quarter of a kilogramme on each half of the wire. The specific resistance after the different amount of stretchings recorded in Experiment XXVIII. was decreased ·03, ·27, ·28 and ·2 per cent. by merely removing the pulley and taking the wire down for the purpose of weighing it in water. These alterations are, it is true, not absolutely large, but if we compare them with the total alteration of specific resistance given in the third column* of the experiment, we see that they are relatively very considerable. Moreover, in this case not the slightest alteration in the length of the wire caused by the removal of the pulley could be detected; neither was the change brought about by the weighing in water, since a similar alteration was caused when the pulley was simply removed and replaced without any such weighing; nor, again, was it due to the restitution of conductivity,

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* The values given in this column are calculated from the resistance determined *after the pulley had been removed and then replaced.*

which we shall learn presently that rest causes after strain, since the resistance was decreased by the removal and replacing of the pulley in one experiment 14 hours after the permanent extension had been made; a much longer time, of course, elapsing in this case than was required in the above mentioned operations.

Again, though the curves are not capable of showing any sudden changes in the ratio of the alteration of the specific resistance, and the extension at the two critical points before alluded to, inasmuch as with most metals these points occur when a comparatively small amount of extension has taken place, yet it will be seen from Experiment XXVIII. that with the increase of length caused by the load of $6\frac{3}{4}$ kilogs. there is a sudden increase of the ratio B : A, and this load corresponds very closely with that at the second critical point of silver.

Hammering.

W. THOMSON, in 1857, experimented on the effects of hammering and permanent extension on the electrical conductivity of copper, and though no actual numbers are given in his paper, states* that "the greatest degree of brittleness produced by tension does not alter the conductivity of the metal by as much as one-half per cent." He, moreover, adds: "A similar experiment showed no more sensible effect on the conductivity of copper wire to be produced by hammering." The foregoing experiments, it will be seen, fairly bear out THOMSON'S statement with reference to the small amount of alteration produced in the specific resistance of copper by longitudinal extension, and show a still smaller change in the resistances of silver and platinum. But since these experiments at the same time showed that the alteration after increasing to a maximum in one direction began to decrease, and in certain cases finally set in in the opposite direction, it seemed desirable to ascertain whether hammering would produce like effects on the specific resistance.

The third of the methods used in determining the change of specific resistance by extension was here employed, except that the wires were now lengthened by hammering them transversely. The last process was accomplished rather by a great number of comparatively small blows than by a less number of large ones, so as to hammer the wire as uniformly as possible throughout its whole length. The following are examples of the results arrived at:—

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* Proc. Roy. Soc., vol. viii., p. 553.

Experiment XXXIII.

A wire of annealed copper, 8 feet in length and ·095 centim. in diameter, hammered transversely throughout its entire length.

Total increase of length per cent. produced by hammering =A.	Total increase of specific resistance per cent. produced by hammering =B.	Ratio of B : A.
1·89	+·017	·009
3·11	+·174	·056
5·95	+·009	·002
9·66	−·209	−·022
16·76	−·530	−·032

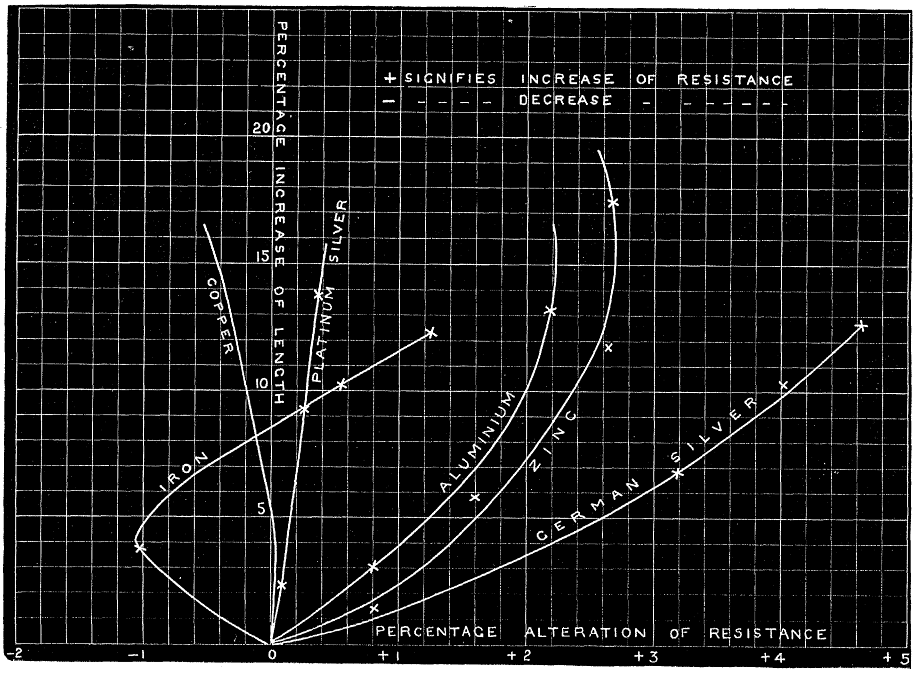
Experiment XXXIV.

A wire of annealed iron, 8 feet in length and ·092 centim. in diameter, hammered transversely throughout its entire length.

Total increase of length per cent. produced by hammering =A.	Total increase of specific resistance per cent. produced by hammering =B.	Ratio of B : A.
2·04	−0·082	−·040
3·94	−1·035	−·263
10·27	+0·554	+·054
12·31	+1·283	+·105

In the next table will be found a series of curves showing the change of specific resistance produced by hammering on the metals iron, copper, zinc, aluminium, German-silver, and platinum-silver. The abscissæ showing the percentage alteration of specific resistance are on a scale of ·05 per cent. for 1 millim., and the ordinates representing the increase of length per cent. are on a scale of ·25 per cent. for 1 millim.

TABLE XVI.—Curves showing the alteration of specific resistance produced by hammering.



Observations on the curves in Table XVI.

Experiments XXXIII., XXXIV., and Table XVI. show that the effect of hammering on the specific resistance is of a somewhat similar character to that of permanent extension. With all the metals, except iron, the specific resistance is at first increased, and this increase, after reaching a maximum, begins to diminish, but with iron the first effect is decrease of resistance which also, after attaining a maximum as the hammering is carried to a greater and greater extent, begins to diminish until finally there is a comparatively large increase of specific resistance.

The changes produced, however, by hammering, though similar in kind to those produced by longitudinal extension, are very different in amount, and a comparison of the two sets of curves and the scales on which they are formed shows that the alterations in the former case are very much greater than those in the latter.

The neutral points also, *i.e.*, the points where the curves cut the axis of ordinates, are different in the two tables, being for copper and iron much higher for the extension than for the hammering, but with zinc and German-silver lower for the extension than the hammering.

Torsion.

As it seemed desirable to supplement the observations of extension and hammering with others on torsion, with the view of ascertaining whether the strain caused by twisting a wire beyond the limits of elasticity would at all resemble the effect produced on the specific resistance by strain set up by the two former processes, a few experiments were made in which the wires having been secured at one end and stretched sufficiently to make them tight, were twisted more and more until they broke.

Experiment XXXV.

A wire of annealed zinc, 8 feet in length and ·095 centim in diameter, twisted.

Amount of torsion; the torsion of a complete revolution in a length of 1 centim. taken as unit = A.	Total increase of specific resistance per cent. produced by the torsion = B.	Ratio of B : A.
·083	+·269	3·24
·167	+·546	3·27
·250	+·376	1·27

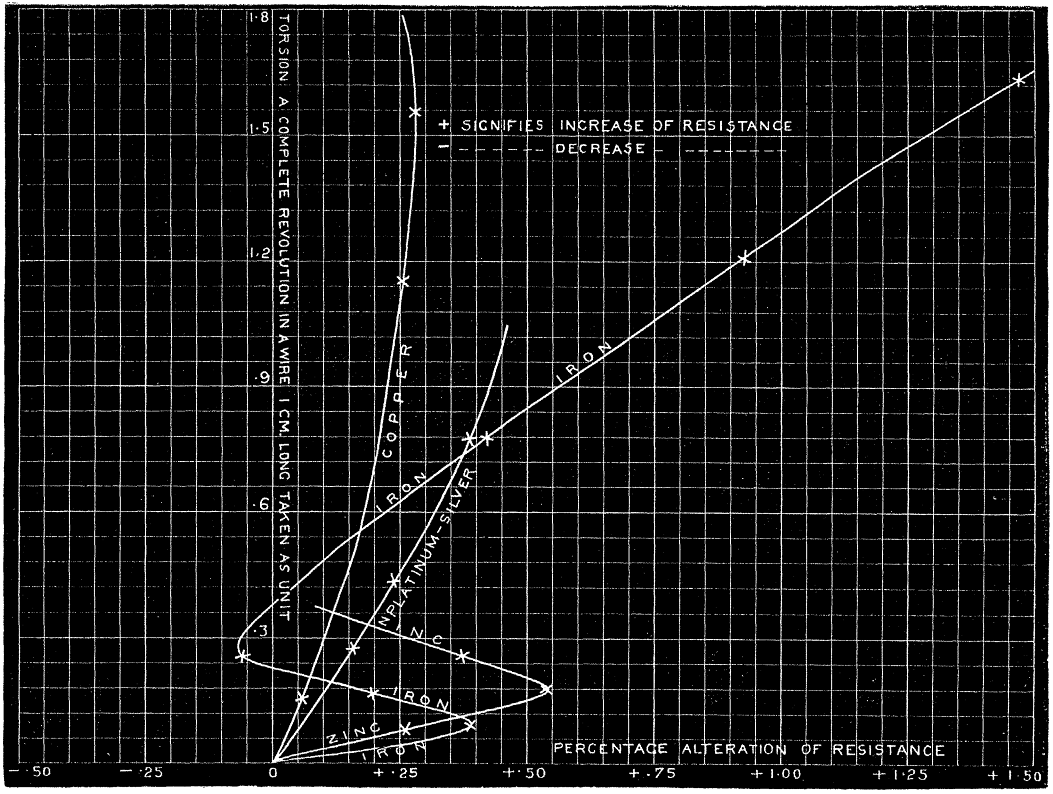
Experiment XXXVI.

A wire of annealed iron, 8 feet in length and ·092 centim. in diameter, twisted.

Amount of torsion; the torsion of a complete revolution in a length of 1 centim. taken as unit = A.	Total increase of specific resistance per cent. produced by the torsion = B. – signifies decrease of specific resistance.	Ratio of B : A.
·080	+ ·394	+4·93
·160	+ ·195	+1·22
·240	– ·053	–0·22
·320	– ·076	–0·24
·800	+ ·413	–0·52
1·200	+ ·928	–0·73
1·600	+1·454	–0·91

In Table XVII. are drawn a series of curves showing the changes produced by permanent torsion in the specific resistance of zinc, iron, copper, and platinum-silver. The abscissæ in these curves represent the percentage alteration of resistance on a scale of ·0125 to 1 millim., and the ordinates representing the torsion in terms of the torsion of a complete revolution in a length of 1 centim. of the wire taken as unit on a scale of ·015 to 1 millim.

TABLE XVII.—Curves showing the permanent alteration of specific resistance produced by permanent torsion.



Remarks on Table XVII.

The effect of torsion on the specific resistance is evidently of a similar nature to that of the effect of permanent extension and hammering, but the amount of alteration shown at the turning point of the curves is in all cases much less than that observed at the turning points of the curves exhibiting the results of hammering and extension. In the case of iron, the first torsion applied increases the specific resistance, but further torsion acts in the same direction as the strain caused by hammering and extension, *i.e.*, diminishes the specific resistance up to a certain point, but beyond this point increases it. It may be that the increase produced in iron by the first few turns is due to magnetic influence on the resistance, for as THOMSON has observed,* the electric current instead of flowing rectilineally along the wire would flow in helical lines, and would therefore increase the resistance by longitudinal magnetization.†

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* W. THOMSON, "Electrodynamic Qualities of Metals," Phil. Trans. 1879, Part I., § 229.

† W. THOMSON, "Electrodynamic Qualities of Metals," Phil. Trans. 1856. Bakerian Lecture, § 146, and H. TOMLINSON, Proc. Roy. Soc., June 17, 1875. [Note added May, 1882.—I have since found that *very slight* extension increases the specific resistance of iron, and am therefore inclined to reject the above hypothesis, and to believe that *very slight* strain of any kind increases the specific resistance.]

It will be noticed also that the curves like those of Tables XV. and XVI. are of parabolic shape.

THE ALTERATION OF SPECIFIC GRAVITY PRODUCED BY PERMANENT EXTENSION, HAMMERING, AND PERMANENT TORSION.

In calculating the values of the specific resistance after the wire had been subjected to any one of the above-mentioned processes, it was in the first instance assumed that there was no change in the specific gravity of the substance, and afterwards a correction applied for such change. The specific gravity of the wires in the annealed condition having been determined, the change wrought by extension, hammering, or torsion carried to an extent which was about three-fourths of that which the substance would bear without rupture was determined by a very delicate balance, and though it was not possible to dislodge any air bubbles which might be attached to the metal when immersed in water by boiling for fear of partially annealing the specimens, these bubbles were brushed off very carefully and considerable pains were taken in the weighings. A very fine platinum wire was used for the purpose of suspending the substances in water, and the vessel employed for holding the water was of considerable size so as to avoid the necessity of bending the wire to any great extent. The coils in which the wire under examination was wound, when weighed, were kept together by fine copper wire, and the weight of this in air and water together with that of the fine platinum wire was from time to time determined. The next experiments show that the change in specific gravity is roughly proportional to the amount of strain, provided this strain is not continued up to the point of rupture.

Experiment XXXVII.

Wire of annealed silver, 8 feet in length and ·090 centim. in diameter, stretched by loading.

Increase of length per cent. =A.	Decrease of specific gravity per cent. =B.	Ratio of B : A.
1·15	·0124	·011
3·64	·0461	·013
7·28	·0892	·012
9·38 (broke)	·1465	·016

Experiment XXXVIII.

A wire of annealed copper, 3 feet in length and ·095 centim. in diameter, twisted.

Number of complete revolutions of torsion =A.	Decrease of specific gravity per cent. =B.	Ratio of B : A.
400	1·16	·0029
600	1·66	·0028
800	2·13	·0027

In Table XVIII. will be found the extent of change in the specific gravity of the different metals produced by a given amount of stretching, hammering, and twisting.

TABLE XVIII.

Name of metal.	Percentage alteration of specific gravity attending a permanent increase of length of 1 per cent. produced by stretching.	Percentage alteration of specific gravity attending a permanent increase of length of 1 per cent. produced by hammering. + signifies increase of specific gravity.	Percentage alteration of specific gravity attending a permanent torsion equal to that of 1 complete revolution in a length of 1 centim. + signifies increase of specific gravity.
Platinum	−·0620	..	..
German-silver . .	−·0612	−·0136	..
Nickel	−·0510	..	..
Zinc	−·0509	−·0146	−·01212
Iron	−·0203	−·0215	−·00283
Silver	−·0156	..	..
Aluminium . . .	−·0082	−·0183	..
Copper	−·0178	+·0065	−·00252
Platinum-silver .	..	+·0159	+·00190

In the last table a − sign signifies a decrease and a + sign an increase of specific gravity.

The specific gravity of all the annealed metals here examined is decreased by permanent extension.*

Hammering also decreased the specific gravity of all the metals subjected to this process except copper and platinum-silver; with these metals the specific gravity was slightly increased.

Permanent torsion decreased the specific gravity of copper, zinc, and iron, and increased that of platinum-silver.

Of the three processes, torsion produced the greatest maximum change in the specific gravity, thus it will be seen from Experiment XXXVIII. that the specific

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* This apparently is not always the case, as Sir W. THOMSON mentions in his article on "Elasticity," 'Brit. Encyc.,' p. 1, that a certain specimen of copper wire annealed in hot sand had its density *increased* more than 1 per cent. by longitudinal extension.

gravity of copper was decreased by the torsion more than 2 per cent.—a large amount considering the small alteration* which extension and hammering can produce.

The results recorded in the last table enabled the previously mentioned correction for change of specific gravity to be made in calculating the specific resistance.

For if Δ_1 and Δ_2 be the specific gravities respectively before and after stretching, hammering, or twisting, and S and x be respectively the specific resistances uncorrected and corrected for change of specific gravity, $x = \mathrm{S} \times \frac{\Delta_1}{\Delta_2}$.

Now the table furnishes the means of determining

$$\frac{\Delta_1 - \Delta_2}{\Delta_1} = \alpha \text{ say ;}$$

and

$$\frac{\Delta_1}{\Delta_2} = \frac{1}{1-\alpha} = 1 + \alpha \text{ very nearly,}$$

since α is very small.

Therefore

$$x = \mathrm{S} \times (1 + \alpha).$$

The correction though small was applied in all cases.

Effect of Cooling Suddenly on the Specific Resistance of Steel.

We have seen in Part I. that the effect of suddenly chilling steel heated to a high temperature produces a somewhat similar effect on the elasticity to that of excessive permanent extension, and it was concluded to be highly probable that whether the distance between the molecules be increased by mechanical strain or by the strain caused by sudden cooling, the elasticity in the direction of the line of separation of the molecules diminishes to a minimum as the separation increases, and then begins to increase. Now BARUS† has proved that the specific resistance of steel *increases* continuously with its hardness, but BARUS's experiments were made with steel heated at or above a visible red, and as the strain produced by extension, hammering, and torsion had been shown to produce up to a certain point *decrease* of resistance, it seemed a matter of some interest to ascertain whether heating the steel to a lower temperature than that of dull red and then cooling slowly would not also have the effect of decreasing the specific resistance. The following experiment was therefore tried :—

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* Not so much as 1 per cent. in any case which I have examined.

† Phil. Mag., November, 1879.

Experiment XXXIX.

A piece of annealed piano-steel wire, 8 feet in length and ·083 centim. in diameter, cooled suddenly by plunging it into cold water after it had been heated to various temperatures.

Condition.	Number proportional to specific resistance.*
Soft.	·91168
Heated and cooled, hiss not audible	·91095
Heated and cooled, hiss just audible	·91094
Heated below dull red but hiss very audible on cooling .	·91118
Heated to dull red and cooled	·91891

In this last experiment the wire was tempered when coiled, the coils being held together by wrapping fine iron wire round them, and passing a burner rapidly round the coils until it was supposed that the requisite temperature had been applied, when the wire was suddenly plunged into water at a temperature of 10° C.

This experiment, though rough as regards the mode of tempering, shows plainly that the specific resistance is *decreased* by the sudden cooling until the tempering is performed at some temperature under dull red, when the specific resistance begins to increase. It will be shown also in Part IV. that the thermo-electric properties of steel are affected in precisely the same manner, that is, that tempering beyond a dull red temperature produces opposite effects to tempering under a dull red temperature.

THE RECOVERY OF ELECTRICAL CONDUCTIVITY PRODUCED BY TIME IN WIRES WHICH ARE IN A STATE OF STRAIN.

In all the experiments described in this Part it was observed that when the wires had been subjected to stresses of any kind, whether purely mechanical or otherwise, which sufficed to produce permanent strain, they invariably gained in electrical conductivity when allowed to rest. The amount of decrease of resistance produced by rest varied however considerably with different metals, being very conspicuous in German-silver and hardly perceptible with platinum-silver.

Table XIX. shows the influence of rest in restoring the electrical conductivity of wires of German-silver, copper, iron, zinc and platinum-silver after hammering so as to increase the length about 15 per cent.; the observations being commenced 20 minutes after the hammering had been completed.

The abscissæ of the curves represent the decrease of resistance on a scale of ·0085 per cent. to 1 millim., and the ordinates on a scale of one hour to the millimetre.

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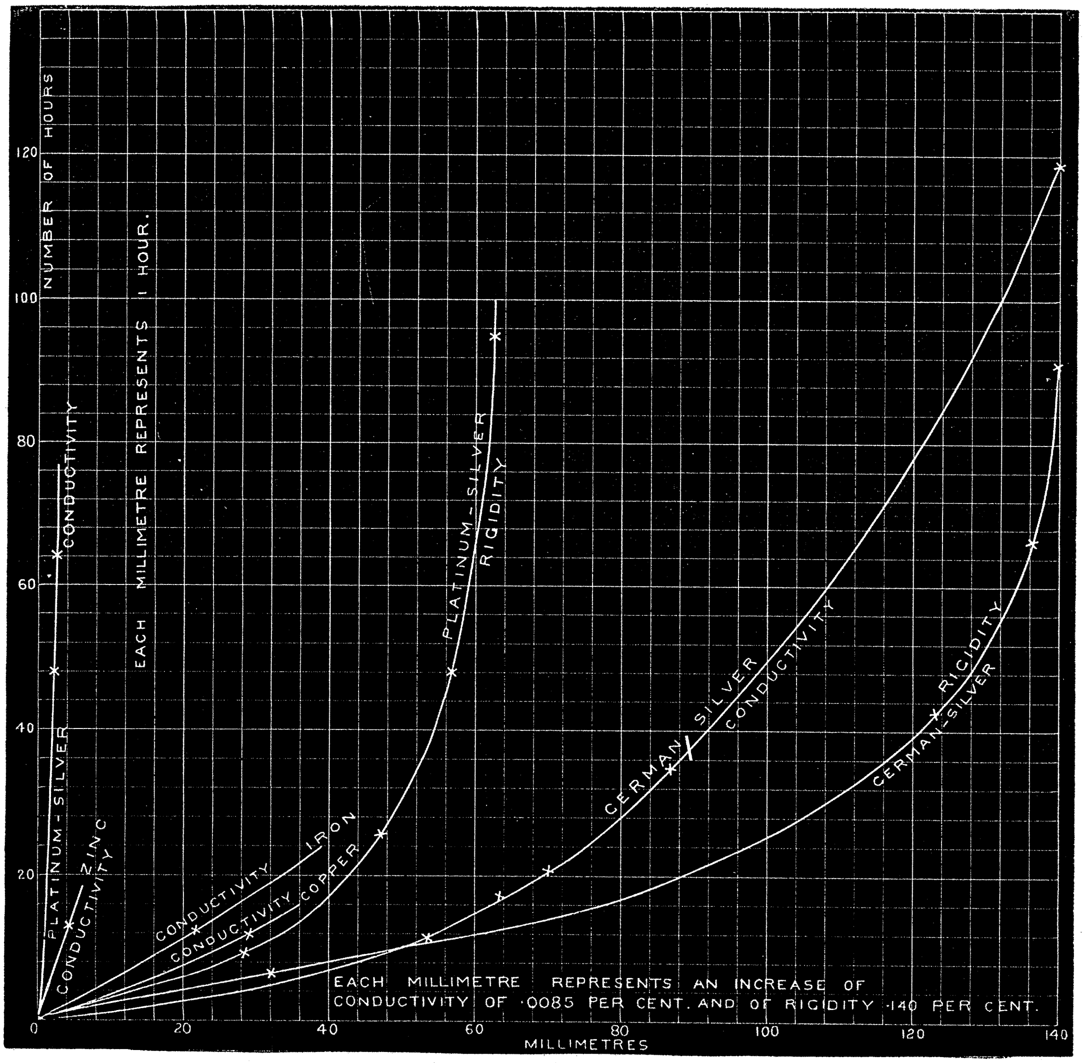
* The resistance of the comparison-wire is here taken as unit.

The tables also show a curve representing the restitution of torsional rigidity in German-silver after hammering, the abscissæ representing the increase of rigidity on a scale of ·0085 per cent. to 1 millim. and the ordinates on the same scale as for the other curves.

TABLE XIX.—Curves showing the recovery of electrical conductivity and of torsional rigidity produced by time in the case of wires which have been hammered transversely.



This table shows the marked difference between German-silver and platinum-silver in respect to the restitution of conductivity produced by rest on these metals when in a state of strain, and this large difference is not confined to strain produced by hammering, but was found to exist also in strain produced by extension, torsion, and wire-drawing, and when taken in combination with the results given in Tables XV., XVI., and XVII. on the alteration of specific resistance produced by strain, shows most conclusively the superiority of platinum-silver to German-silver in making standard resistance coils.

We have seen also in Part I. that rest, materially in some cases and to a certain extent in all, increases the elasticity of metals; now German-silver wire furnishes a conspicuous example of this; and the curve in the table representing the increase of torsional rigidity produced by rests, shows plainly that the restitution of elasticity and electrical conductivity go hand in hand. And this circumstance, when taken in conjunction with the fact that there is no change in the dimensions of the wire which would at all account for the increase of elasticity or conductivity, evidently teaches us that when we can increase the elasticity without altering the mean molecular distance, we at the same time increase the electrical conductivity.

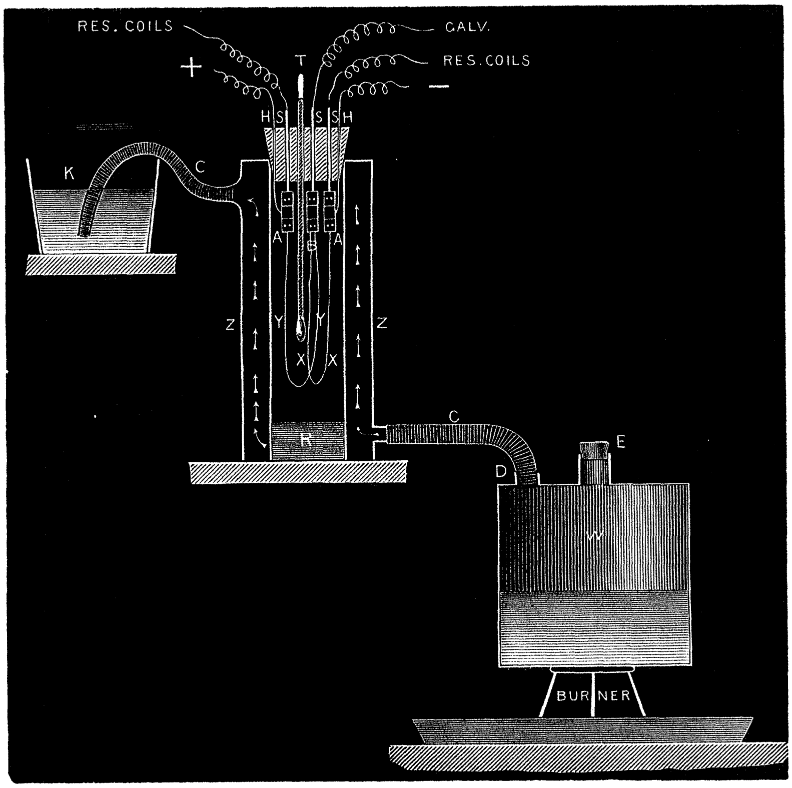
THE INFLUENCE OF PERMANENT STRAIN ON THE CHANGE OF ELECTRICAL CONDUCTIVITY PRODUCED BY ALTERATION OF TEMPERATURE.

Permanent extension, hammering, and torsion.

The previous observations on the change of specific resistance produced by extension, hammering, and torsion having given rise to the suspicion that these processes caused the wires to alter their susceptibility to change of resistance from change of temperature, and that this alteration of susceptibility bore a marked relation to the alteration of the thermo-electrical properties which are also caused by stress and strain, it was considered very advisable to further investigate the matter.

In the first few trials the large air chamber previously described was employed, but the changes wrought in the coefficient of increase of resistance from rise of temperature by the various strains were found to be so small that special precautions had to be taken to secure reliable results. Accordingly the following apparatus was made use of. In the figure Z Z is an air chamber made of two concentric brass tubes 12 inches in length. The diameter of the wider tube is 4½ inches, and of the inner tube 2½ inches, so that the two enclose between them a layer of air 1 inch thick. The two tubes are connected at the top and bottom by brass rings soldered to them, and two pieces of brass tubing soldered into the outer cylinder, one near the bottom and the other near the top, communicate by means of indiarubber tubing with a boiler, W, and a vessel of cold water, K, respectively, so that steam from the boiler can fill the entire space between the two concentric cylinders and be condensed in K. Three stout wires of copper, S S S, 4 inches in length, pass through a cork which fits tightly the inner cylinder, and their upper ends are connected with the resistance coils and galvanometer, whilst to their lower ends are attached three clamps, A A and B. To the clamps are soldered silk-covered copper wires, which, passing through the cork, are connected with the poles of the battery. The ends of the wire to be tested, X, and the comparison-wire, Y, are secured to the clamps at A A and B, the two wires having previously to clamping been enveloped in cotton tubes of the same lengths as the wires. As a further precaution, the clamps A were well wrapped up in silk, and with the wires were enclosed in a cardboard cylinder which fitted neatly into the inner brass cylinder. When it was necessary to heat the wires, jackets of several folds of baize were placed round the outside of the air chamber and also completely covered the top.

Fig. 17.



The connexions with the resistance coils of 100 ohms and the galvanometer were exactly as in previous experiments, so that from the disposition of the wires as shown in the figure, it will be seen that the influence of change of temperature on the connexions would be entirely neglectable. Moreover, the boiler and air chamber, which were some distance from the box of resistance coils, were screened from the latter, which was covered on the outside with tin foil, and only opened at the moments of actual testing for the balance between X and Y. The wires X and Y were in all cases 50 centims. long, and so disposed that they occupied the central portion of the chamber; whilst a thermometer, T, served to indicate the temperature. The air chamber stood upright on a table, and the lower portion of it, R, was packed with sawdust on which the base of the cardboard cylinder rested.*

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* It would have been better to use a cylinder of copper foil instead of the cardboard, as thereby the temperature would have been rendered more uniform throughout the length of the wire.

The mode of experimenting adopted was as follows: X and Y having been placed in position and the air chamber covered with its baize jackets, the balance between the two wires was observed, and the thermometer having been pulled sufficiently far out of the cork to enable one to take the reading of the temperature, was afterwards replaced. The water in W was then boiled, and in about half an hour the air in the chamber was found to be at 100° C., and was allowed to remain so for another half an hour, when X and Y were again balanced. The burner was next taken from under W, when a vacuum was formed in the upper part of the boiler by the steam condensing; this vacuum was at once filled by the atmospheric pressure forcing water from K, and when the space between the two brass cylinders had in a short time become filled with the water from K, the cork E was removed from the boiler, and a siphon action allowed to continue from K which was kept supplied with cold water. The jackets were then removed, and the cork E having been replaced, the whole arrangement was suffered to rest for two hours, when the thermometer indicating the temperature of the air chamber to be within a degree or so of the original temperature, the balance between X and Y was once more determined. As the processes of hammering and stretching by increasing the length of X might possibly have caused an error by making the lower portion of the wire to occupy a lower position in the chamber than the corresponding portion of Y,* the former wire was from time to time shortened to the same length as the latter. Also, since with all the wires it was found impossible, even by using the greatest care in annealing, to find two pieces of the same wire which would agree exactly in their co-efficients of increase of resistance, these were compared before X was subjected to strain of any sort. The following experiments illustrate the nature of the results obtained:—

Experiment XL.

An annealed copper wire, ·095 centim. in diameter, was stretched by hand permanently to different extents, and after each stretching tested for alteration of resistance from change of temperature.

Percentage increase of length.	Percentage of average temporary superior increase of resistance of stretched wire over unstretched for 1° C. between 20° C. and 100° C. + signifies superior increase of stretched wire on rise of temperature.	Percentage of average permanent decrease of resistance for 1° C. between 20° C. and 100° C. of stretched wire.
5·83	−·00046	·00104
11·40	−·00074	·00107
22·27	−·00045	·00354
32·73	+·00378	·00190

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* I have found it very difficult even with such an arrangement as the above to get an *exactly* uniform temperature, except in the central portion of the chamber.

Experiment XLI.

An annealed iron wire, ·0065 square centim. in section, stretched by hand.

Percentage increase of length.	Percentage of average temporary superior increase of resistance of stretched wire over unstretched for 1° C. between 20° C. and 100° C. + signifies superior increase of stretched wire on rise of temperature.	Percentage of average permanent decrease of resistance for 1° C. between 20° C. and 100° C. of stretched wire, – signifies permanent increase.
6·0	+·0071	–·00165
12·0	+·0055	+·00230

Experiment XLII.

An annealed copper wire, ·095 centim. in diameter, hammered.

Percentage increase of length.	Percentage of average temporary superior increase of resistance of hammered wire over unhammered for 1° C. between 20° C. and 100° C. + signifies superior increase of hammered wire on rise of temperature.	Percentage of average permanent decrease of resistance of hammered wire for 1° C. between 20° C. and 100° C.
1·74	–·00340	·00836
5·81	+·00117	·00603
11·05	+·00122	·00447
21·36	+·00139	·00072

Experiment XLIII.

An annealed iron wire, ·063 centim. in diameter, hammered.

Percentage increase of length.	Percentage of average temporary superior increase of resistance of hammered wire over unhammered for 1° C. between 20° and 100° C. + signifies superior increase of hammered wire on rise of temperature.	Percentage of average permanent decrease of resistance of hammered wire for 1° C. between 20° and 100° C.
6·13	+·0009	·0033
10·72	+·0000	·0056

Experiment XLIV.

An annealed copper wire, ·095 centim. in diameter, permanently twisted.

Torsion in terms of a unit taken as the torsion in a wire 1 centim. long when twisted through one revolution.	Percentage of average temporary superior increase of resistance of twisted wire over untwisted for 1° C. between 20° and 100° C. + signifies superior increase of twisted wire on rise of temperature.	Percentage of average permanent decrease of resistance of twisted wire for 1° C. between 20° and 100° C.
0·652	–·000797	. .
1·087	–·000824	·00003
3·261	–·000977	·00015
6·520	+·002097	–·003074

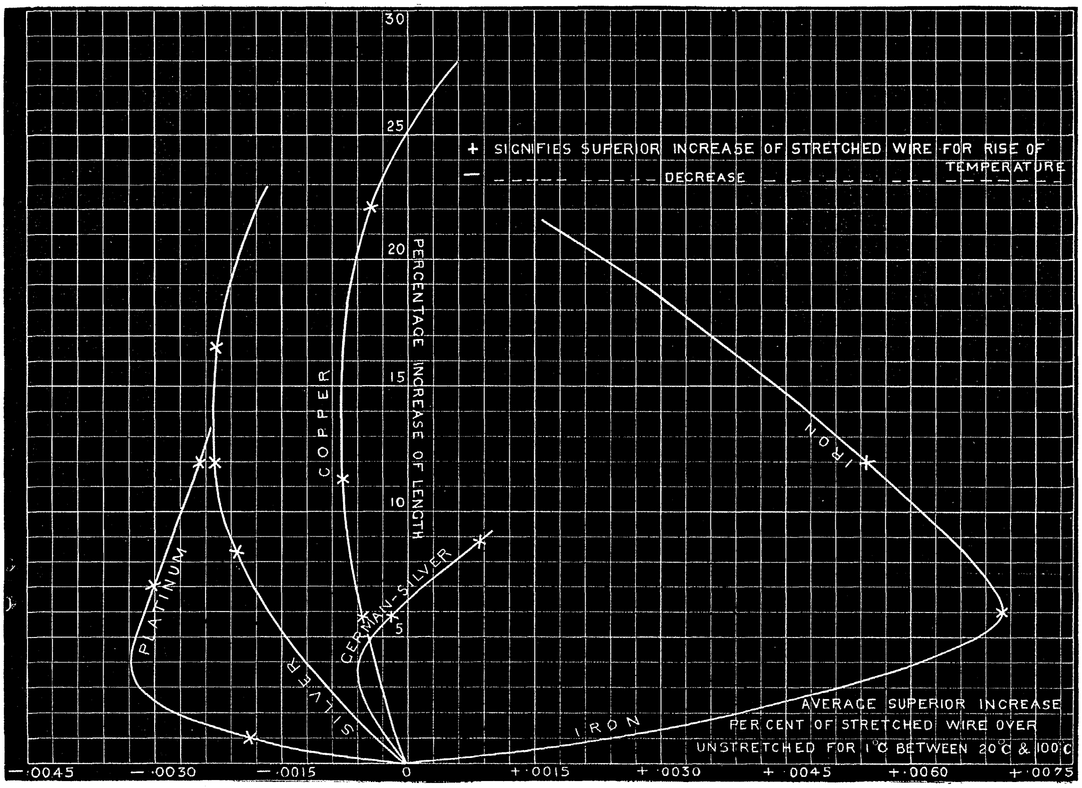
Experiment XLV.

An annealed iron wire, ·063 centim. in diameter, permanently twisted.

Torsion in terms of a unit taken as the torsion in a wire 1 centim. long when twisted through one revolution.	Percentage of average temporary superior increase of resistance of twisted wire over untwisted for 1° C. between 20° and 100° C. + signifies superior increase of twisted wire on rise of temperature.	Percentage of average permanent decrease of resistance of twisted wire for 1° C. between 20° and 100° C.
0·260	+·00474	·00025
1·090	+·00421	·00050
2·180	+·00092	·00100

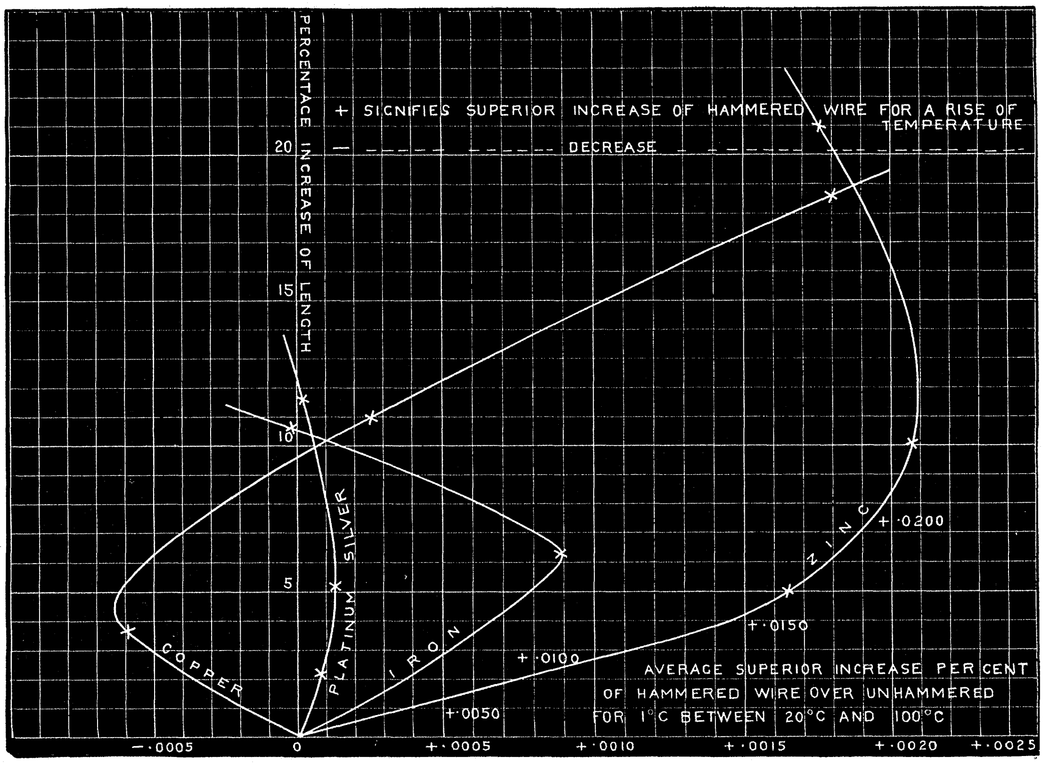
The effect of permanent extension, of hammering, and of torsion on the alteration of resistance produced by change of temperature in the case of copper, of iron, and of other metals is shown in Tables XX., XXI., and XXII.

Table XX.—Curves showing the effect of permanent extension on the temporary alteration of electrical resistance produced by change of temperature.



In Table XX. the curves have their abscissæ representing the average superior increase of resistance for a rise of 1° C. of the stretched wire on a scale of ·000075 percentage of superior increase for each millimetre, and in Table XXI. the curves are drawn with their abscissæ representing the average superior increase of resistance of the hammered wire for a rise of 1° C. on a scale of ·000025 percentage of superior increase for each millimetre. In both sets of curves the ordinates represent the percentage of permanent increase of length on a scale of ·25 percentage of increase of length for 1 millim.

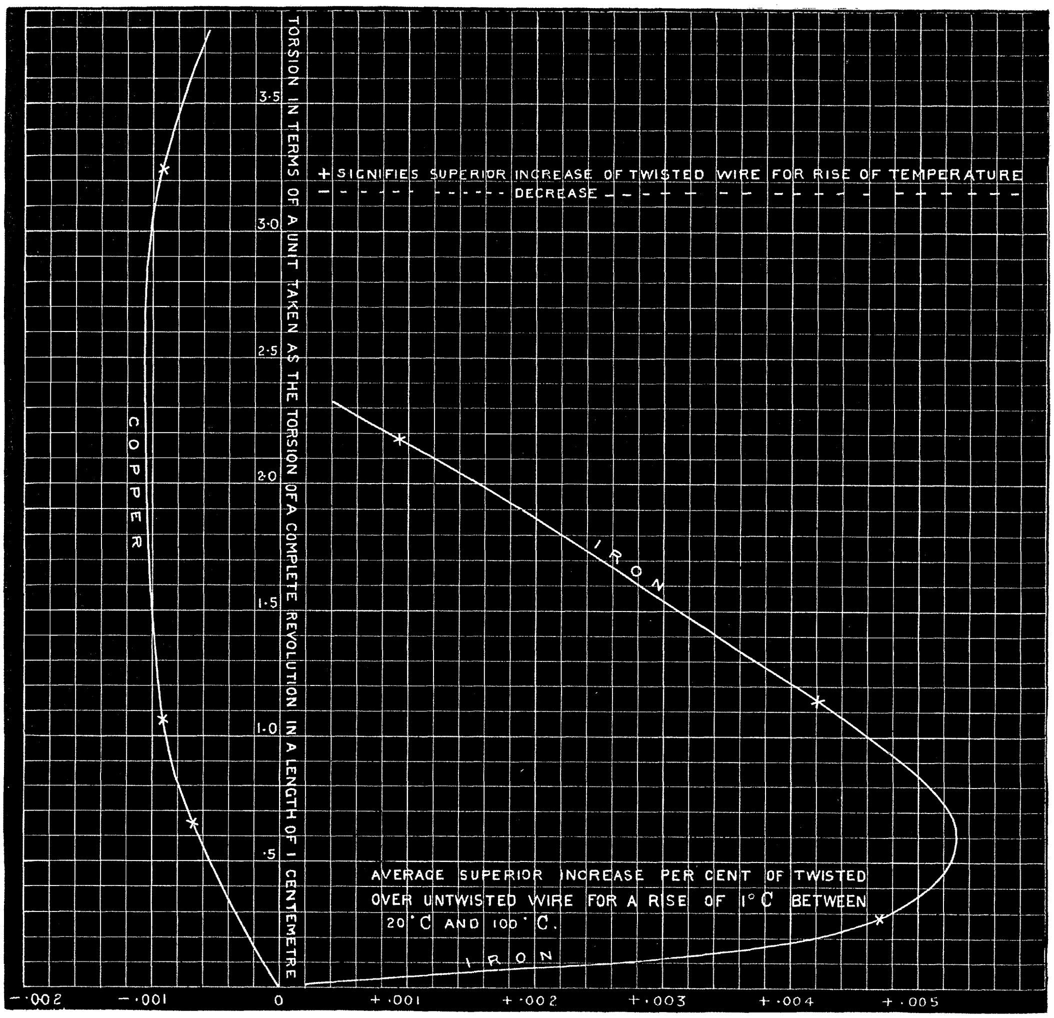
Table XXI.—Curves showing the effect of hammering on the temporary alteration of electrical resistance produced by change of temperature.



For zinc the abscissæ represent 10 times as much alteration of resistance as they do for the other metals.

In Table XXII. the abscissæ of the curves represent the superior increase of resistance of the twisted wire on a scale of ·0005 percentage of superior increase for each millimetre, and the ordinates the amount of permanent torsion in terms of a unit taken as the torsion of a complete revolution in a length of 1 centim. on a scale of ·025 unit for 1 millim. In all the tables a + sign before an abscissa signifies that the strained wire increases most on rise of temperature, and the values of these abscissæ were determined as follows:—Let $\frac{A}{B}$ and $\frac{A'}{B'}$ represent the ratios of the wire to be tested, and the comparison-wire at any two temperatures t and t'; then the average percentage superior change of resistance is $\dfrac{\left(\pm\frac{A'}{B'}\mp\frac{A}{B}\right)\times 100}{(t'-t)\times\frac{A}{B}}$, t' being the higher of the two temperatures, which were about 100° C. and 20° C.

TABLE XXII.—Curves showing the effect of permanent torsion on the temporary alteration of electrical resistance produced by change of temperature.



Remarks on the last experiments and tables.

The first point to be noticed is that the metals examined may be divided into two classes. In the first of these classes, which includes iron, zinc and platinum-silver,*

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* In some experiments made by H. A. TAYLOR (see "Report of Electrical Standards Commission," Appendix II., Brit. Ass., York Meeting, 1881), the effect of drawing platinum-silver wire to finer and

the strained wire is *most increased in resistance* by rise of temperature up to a certain limit of straining; whilst beyond this limit further strain diminishes the first effect. In the second class, which comprises copper, silver, platinum and German-silver, the strained wire is *least increased in resistance* by rise of temperature, but that, here again, after a certain limit of strain has been reached the first effect begins to be diminished. Now it will be shown in Part IV. that the metals of the first class, when subjected to a moderate amount of strain, whether the latter be produced by permanent extension, hammering, or torsion, or by other than purely mechanical means, are *thermo-electrically positive* to pieces of the same metal unstrained, and that the first effect is ultimately reversed if the strain be carried to excess; whilst the metals of the second class are, when moderately strained, *thermo-electrically negative* to unstrained pieces of the same metal, but when subjected to excessive strain become thermo-electrically positive. We are therefore led to the conclusion that there must be some close relationship between the thermo-electrical properties of metals, and their temporary alteration of resistance from change of temperature, and that *strain renders a piece of metal thermo-electrically positive or negative to a piece of the same metal unstrained according as the strained piece is caused to be less or more increased in electrical resistance by rise of temperature.*

Another point to be considered is that the metal which is *increased* in specific resistance by the strain is not always rendered *less* susceptible to change of resistance from alteration of temperature, for, as we have seen, zinc and platinum-silver are increased in specific resistance by moderate strain, and are yet at the same time rendered more susceptible to alteration of resistance from variations of temperature. With the former of the above-mentioned metals, the alteration of susceptibility to change of resistance from change of temperature is comparatively much larger than is the case of any of the other metals; whilst with platinum-silver the effect of strain in this respect is comparatively slight, and of the opposite kind to that which is produced on its two constituents.

Again, the third column in the experiments shows that the permanent effect produced by the change of temperature is not of the same nature with iron as with copper; with the former metal the resistance is in some cases actually increased by the annealing when the strain is moderate, and in those cases where a permanent decrease of resistance is caused this increases with increased strain; with the latter, on the contrary, permanent decrease of resistance after moderate straining is the result of the annealing, and this decrease after increasing to a maximum begins to become less with further strain. The difference between iron and copper in the above-mentioned respect is readily intelligible when we remember that these metals differ as regards the kind of alteration of specific resistance caused by strain, as we have seen that with iron the

finer gauges was found to be to diminish the temperature coefficient, but it seems that Mr. TAYLOR annealed the wires after the process of drawing.

specific resistance is decreased by moderate strain but increased by excessive strain; whilst with copper, moderate strain effects increase, and excessive strain, decrease of resistance.

THE EFFECT OF TEMPORARY STRESS ON THE ALTERATION OF ELECTRICAL RESISTANCE PRODUCED BY CHANGE OF TEMPERATURE.

As permanent strain had been proved to alter the susceptibility to change of resistance from change of temperature in a manner which suggested an intimate relationship between this susceptibility and the thermo-electric properties of metals, some attempts were made to determine the effect of such temporary stress as could be caused by longitudinal traction, on the alteration of resistance produced by change of temperature, partly with a view of establishing a still closer relationship between the above-mentioned physical qualities, and partly with the object of ascertaining whether the increase of elasticity which WERTHEIM's experiments[*] seemed to have proved to be produced in iron and steel when the temperature is raised from 20° C. to 100° C., would be rendered manifest in experiments on the influence of stress on the electrical resistance. The difficulties here encountered seemed at first sight to be so great as to render it an almost impossible task to *measure* with any approach to accuracy the effect sought, unless this effect should be something very appreciable compared with the percentage alteration of resistance produced by stress at ordinary temperatures; for, as we have already seen, the increase of resistance produced by raising the temperature to 100° C. would be some hundreds of times greater than any change of resistance which can be produced in most metals by mechanical stress. After several failures, however, these difficulties were overcome, and I succeeded in measuring with almost the same accuracy the comparatively minute alterations of resistance produced by temporary longitudinal traction at the temperature of 100° C. as at the ordinary temperature of the room.

To accomplish the desired object the large air chamber used in the first part of the enquiry was provided with two tubes, one near the bottom and the other near the top; these tubes served the purpose of conveying steam into the bottom of the outer of the two cylindrical chambers of which the vessel consisted, and out again, near the top of the vessel, into a tub of cold water, a hole at the top of the chamber which had been used previously for the purpose of filling the chamber with water having been corked up after the water had been emptied out. The air chamber was wrapped round with several layers of baize, and these in turn surrounded with several layers of paper tied round with string. The top of the air chamber was also well covered in the same manner with baize and paper, and the table on which the air chamber rested was surrounded on all sides with like material with the exception of a small aperture

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[*] Ann. de Chimie et de Phys., 3^{me} série, 1844, p. 431.

through which the experimenter was enabled to adjust the weights on the scale-pan attached to the wire to be tested. The scale-pan was suspended from the pulley, which was 6 inches from the bottom of the chamber, by a wire sufficiently strong to bear the weights employed, and this wire passed through a hole in the table only just large enough to allow of free motion. The doors and windows of the room were kept shut during the testing at the higher temperature, and the usual precautions were taken to avoid any risk of permanent set or any liability to change of elasticity from testing too soon after permanent extension. In about an hour after the first entrance of the steam into the air chamber the temperature of the air at the top and bottom was nearly, if not quite, at 100° C., but it was found necessary to allow the steam to enter for three or four hours before the wire to be experimented on and the comparison-wire had assumed a sufficiently stable resistance-ratio, and even after this time there would be slow and very minute variations of this ratio first in one direction and then in the opposite. Any errors, however, which would result from slow and minute variations were got rid of in the following manner :—Let a_1, b_1 ; a_2, b_2, &c., be the apparent alterations produced by putting on and taking off the load several times in succession ; then the true alterations due to the load will be very nearly

$$\frac{a_1+a_2+2b_1}{4}, \frac{b_1+b_2+2a_2}{4}, \text{\&c.}$$

The following experiment will show how accurately the measurements could be made even at the temperature of 100° C.

Experiment XLV.

An annealed iron wire, 7 feet in length and ·067 centim. in diameter, was loaded and unloaded several times with a weight of 3 kilogs. ; this weight was then removed and a rest of 48 hours allowed, when, on again testing with 3 kilogs., the recovery was found to be quite perfect. The wire was then heated to 100° C., and having been maintained at this temperature for several hours was again tested. Afterwards the air chamber was suffered to cool down to the original temperature of 13° C. and after a rest of 24 hours the elasticity was redetermined with the same load as before.

Number of trial.	Alteration of resistance in terms of the divisions of the platino-iridium wire produced by 3 kilogs. at 13° C.	Alteration of resistance in terms of the divisions of the platino-iridium wire at 100° C.	Alteration of resistance after cooling again to 13° C.
1	51·85	51·13	51·25
2	51·85	51·25	51·33
3	51·88	50·25	51·27
4	51·98	49·80	51·18
5	52·02	51·65	51·08
6	51·80	53·15	..
7	51·82	52·00	..
8	51·73	51·75	..
9	52·38	50·33	..
10	52·08	50·22	..
11	51·85	50·75	..
12	51·92	51·15	..
13	..	52·43	..
14	..	52·43	..
Mean	51·93	51·30	51·23
Probable error per cent.	·06	·16	·03

It will be observed that even at 100° C. the probable error does not amount to ·2 per cent., and, moreover, besides the set of readings recorded in the experiment two others of a similar kind were made afterwards, giving mean values of 51·21 and 51·26, and a total mean of 51·28 as the alteration of resistance caused by a load of 3 kilogs. at 100° C., as against 51·23, the alteration produced on cooling again to 13° C.

Experiment XLVI.

The same wire was again heated to 100° C. and tested with loads of 1, 2, and 3 kilogs., and afterwards, having cooled down to 16° C., the effects of the same loads were redetermined.

Number of kilogs. in the load.	Alteration of resistance produced by the load at 100° C.	Average alteration per kilog. at 100° C.	Alteration of resistance after cooling for 24 hours to 16° C.	Average alteration per kilog. at 16° C.
1	16·89	16·89	17·40	17·40
2	35·82	17·91	34·33	17·17
3	54·99	18·33	51·62	17·21

Experiment XLVII.

The same wire was treated with a load of 6 kilogs. in exactly the same way as it had been treated when 3 kilogs. were employed, and afterwards tested with loads from 1 to 6 kilogs.

Number of kilogs. in the load.	Alteration of resistance at 12° C.	Average alteration per kilog. at 12° C.	Alteration of resistance at 100° C.	Average alteration per kilog. at 100° C.	Alteration of resistance after cooling for 24 hours to 12° C.	Average alteration per kilog. at 12° C.
1	16·96	16·96	18·60	18·60	17·42	17·42
2	33·81	16·92	37·25	18·63	35·53	17·77
3	51·97	17·32	55·92	18·57	52·50	17·50
4	69·98	17·50	75·02	18·76	70·80	17·70
5	86·03	17·21	92·84	18·57	88·45	17·69
6	102·84	17·13	111·95	18·66	106·10	17·68
Mean values	..	17·17	..	18·63	..	17·63

Experiment XLVIII.

The same wire after having been heated to 100° C., and kept at this temperature for several hours with a load of 6 kilogs. on it, was allowed to cool, and in 24 hours the alteration of resistance produced by the cooling observed.

Similar processes were employed with loads of 5 kilogs. and of 3 kilogs.

Number of kilogs. left on the wire when cooling.	Superior alteration of resistance of stretched wire produced by the cooling from 100° C. to 13° C. — signifies superior decrease of resistance of stretched wire on cooling.
6	−8·8
5	−8·0
3	−6·6

Experiment XLIX.

An annealed copper wire, 7 feet in length and ·095 centim. in diameter, treated in a manner similar to that in which the last iron wire had been treated, and tested at 12° C. and 100° C. with a load of 5 kilogs.

Temperature in degrees Centigrade.	Alteration of resistance in terms of the divisions of the platino-iridium wire produced by 5 kilogs.
12°	42·13
100	45·34
12	44·31
100	45·14

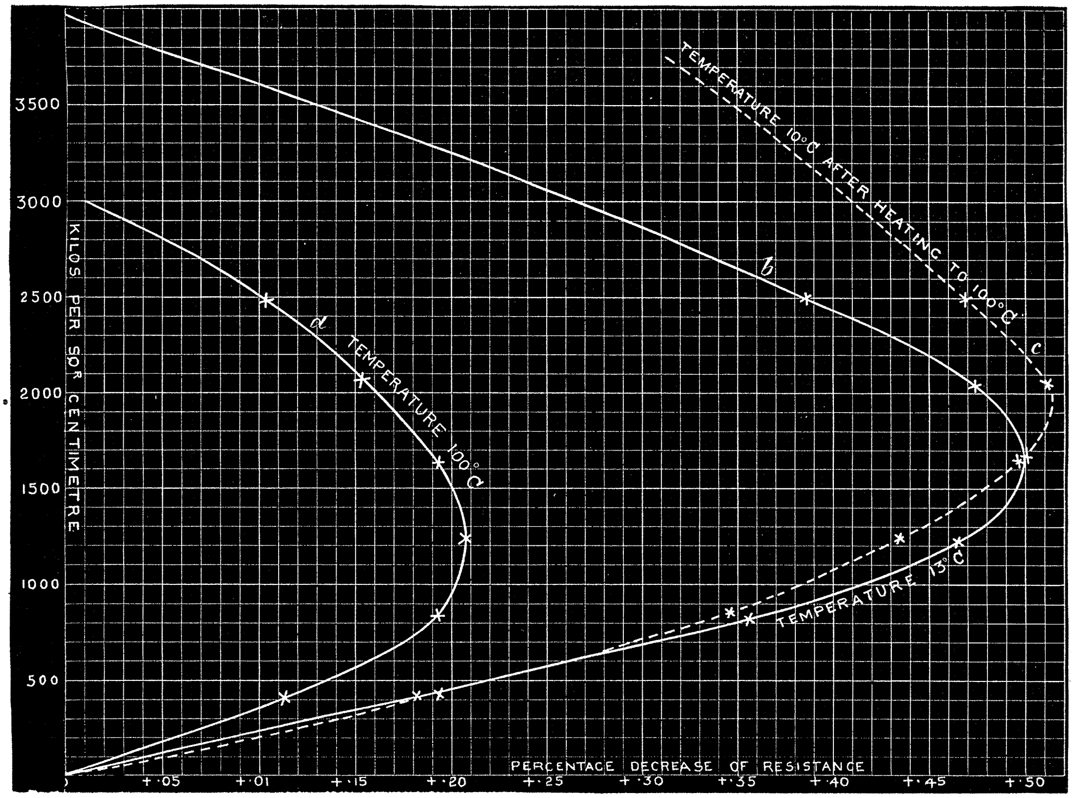
Experiment L.

A piece of the same nickel wire, which had been previously broken by testing for alteration of resistance at the ordinary temperature of the room, was annealed again and adjusted in the air chamber in the manner previously described. A load of 18 kilogs. was then suffered to remain on the wire for several minutes, and after its removal the nickel was allowed to rest unloaded for 24 hours. The wire was now tested with loads up to 12 kilogs. at the temperature of 13° C., then after heating to 100° C., and again, 24 hours afterwards, when cooled to 10° C.

Load in kilogs.	Alteration of resistance at 13° C. in terms of the divisions of the platino-iridium wire. – signifies decrease of resistance of stretched wire.	Alteration of resistance at 100° C.	Alteration of resistance after cooling to 10° C.
2	– 58·3	–36·1	– 60·6
4	–114·0	–62·8	–110·0
6	–148·4	–68·2	–137·7
8	–159·1	–62·5	–155·9
10	–151·3	–49·6	–160·7
12	–123·8	–33·8	–149·4

The effect of change of temperature on the temporary decrease of resistance produced by loading is also shown in Table XXIII.

TABLE XXIII.—Curves showing the temporary alteration of electrical conductivity of nickel produced by longitudinal traction at temperatures of 10° C., 13° C., and 100° C.



Remarks on the last experiments and on Table XXIII.

Experiment XLV. teaches us that though the alteration of resistance of the iron when loaded with 3 kilogs. is greater at 13° C. *before heating to* 100° C. than at 100° C.; yet, *after cooling again to* 13° C., the alteration is very slightly *less* than it had been at 100° C., and, on the whole, there is a *permanent* decrease of the temporary alteration of resistance produced by the loading. From Experiment XLVI. we learn that the second heating to 100° C. still further increases the difference of the effect of loading with 3 kilogs. at the lower and the higher temperatures; the alteration at the *higher* temperature being now more than 6·5 per cent. *greater* than at the *lower* temperature; but when the load employed is only 1 kilog., the alteration seems to be greater at the lower temperature than at the higher. Experiment XLVII. shows that when the wire was treated with 6 kilogs. there was a permanent increase of elasticity produced by the loading, and it should at the same time be noted that 6 kilogs. when first put on the wire, *barely produced a permanent increase of length*—an increase certainly not amounting to more than $\frac{1}{10}$th per cent. By comparing also columns two and six we can see that the slight annealing caused by raising to 100° C., and cooling again has diminished the elasticity, and therefore we have evidence here that *very slight extension* permanently increases the elasticity of iron; whilst in Part I. we have seen that moderate permanent extension decreases, and excessive permanent extension increases the elasticity of iron. It is evident, therefore, that we have three critical points in iron wire, and that the elasticity is first increased to a maximum, then decreased to a minimum, and finally begins to increase again as the permanent extension is gradually increased from exceedingly small amounts to the breaking point of the wire.

Again, the alteration of resistance produced by *all* the loads is now *greater* at 100° than at 12° by amounts varying from about 5 to 6 per cent.

Experiment XLVIII. also shows that when loads from 6 to 3 kilogs. are left permanently on the wire when cooling from 100° C. to the temperature of the room, the alteration of resistance decreases as we decrease the load, and bears out the previous observations that the elasticity is less at the higher than at the lower temperatures.

In Experiment XLIX. we have evidence that the slight annealing caused by raising the temperature of the copper to 100° C. permanently decreases the elasticity, and that the alteration of resistance at 100° C. is for the load employed about 2 per cent. greater than at 12° C. It is, however, when we come to Experiment L. that the most noticeable changes are seen to be produced, and when we consider the results recorded in this experiment and in Table XXII. we are led to the conclusion that the temporary alteration of susceptibility to change of resistance from changes of stress effected by raising to 100° C. is, with nickel, as remarkable as we have seen this susceptibility itself to be. The curves are drawn on the same scale as the curves for nickel at 22° C., and it will be observed that not only is the maximum diminution of resistance lessened by raising to 100° C. to an amount which is *less than one-half* of the maximum diminution at the lower temperature, but that also the load at which this maximum diminution occurs is much less; and it may well be that at a sufficiently high temperature the decrease of resistance which is observed to be produced by moderate loads at the lower temperatures would be changed to an increase. In fact, I am inclined very strongly to believe that there exists with all metals a critical temperature below which temporary stress will produce temporary decrease of resistance, and that above this temperature there is an opposite effect caused by the stress.

The value of "YOUNG'S modulus" was determined for this piece of nickel by the method of static extension, in a manner to be presently described, and was equal to 2480×10^6 at the temperature of 16° C. and to 2280×10^6 at the temperature of 100° C. It will be observed that the maximum decrease of resistance as shown in Table XXIII., is appreciably greater than the maximum decrease observed with the other specimens,* and still further shows how the amount of this decrease depends upon the elasticity.

As regards the question whether the thermo-electric properties of the metals, as

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* These two specimens were received at different times from Messrs. JOHNSON, MATTHEY, & Co., and the latter shows still more remarkably than the former the large elasticity which can be obtained from nickel even in a well-annealed condition.

affected by temporary stress, be related to the susceptibilities of alteration of resistance from change of temperature in the same way as the corresponding qualities seem to be where permanent strains are concerned, it may be said to remain at present open, and only to be decided by further experiments on the effects of stress on the thermo-electric qualities of iron;[*] but as far as copper and nickel are concerned, the above question seems to be answered in the affirmative.

THE EFFECT OF SLIGHT MECHANICAL STRAIN AND OF THE STRAIN CAUSED BY RAISING IRON TO 100° C. AND AFTERWARDS COOLING, ON THE TORSIONAL RIGIDITY OF THE METAL.

The above experiments had shown such an astonishing influence to be produced on the longitudinal elasticity of annealed iron by merely raising the metal to 100° C. and then cooling, that it seemed advisable to test whether or not a similar effect would be produced on the torsional rigidity of iron by a like cause, and if so, whether we can imitate the strain resulting from heating and afterwards cooling by mechanical means.

Experiment LI.

A piece of annealed iron wire was vibrated at a temperature of 13° C., and the time of a single vibration, as determined by counting the vibrations for five minutes, was found to be 1·000 second. The wire was then heated in an air chamber to 100° C., and after having been maintained at this temperature for one hour was suffered to cool, and the time of vibration found to be 0·989 second 12 hours after cooling.

Experiment LII.

A second piece of the same wire, when suspended ready for vibrating, was heated slightly by passing the flame of a BUNSEN burner rather quickly up and down it several times, the vibrator being at the same time supported, so as to take off stress from the wire. The time of vibration before heating was 1·154 second, and in five minutes, 35 minutes, and 245 minutes after cooling was 1·147, 1·142, and 1·136 second respectively.

The wire was then heated to redness and cooled, when the time of vibration after five minutes was 1·156 second, and after 22 hours became 1·143 second.

Experiment LIII.

A third piece of the same wire was vibrated after different slight amounts of permanent extension had been produced; the length before stretching was 82·0 centims., and the time of vibration 1·621 second. After slightly stretching, so as to increase the length to 82·2 centims. and 84·3 centims., the time of vibration became respectively 1·614 second and 1·714 second.

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[*] This point will be fully considered in Part IV.

Experiment LIV.

A piece of annealed pianoforte steel was vibrated after different slight amounts of permanent extension.

Length of wire, in centims.	Time of vibration, in seconds.
89·00	·984
89·05	·976
89·10	·968
89·20	·968

These experiments* speak for themselves, and prove that the torsional rigidity is affected in a precisely similar manner to the longitudinal elasticity by raising to 100° C., and then cooling, and moreover that the strain produced by slight mechanical traction acts in a similar manner on both iron and steel to the strain produced by tempering. We see also how very quickly the increase of elasticity is changed into a decrease when the extent of strain is widened either by heat or by mechanical means. Evidently then there are for iron three critical points as regards its torsional rigidity as well as regards its longitudinal elasticity—very slight strain increasing, moderate strain decreasing, and excessive strain again increasing both these physical properties. Further, it would be interesting to determine whether cold would not produce the opposite effect on the elasticity to heat, and it seems highly probable that cooling below the temperature of the room will permanently decrease the elasticity of iron; this point, however, I hope to be in a position shortly to decide.

FURTHER DISCUSSION OF WERTHEIM'S EXPERIMENTS ON ELASTICITY.†

We have seen that the temporary alteration of resistance produced by any load is permanently decreased in the case of annealed iron wire by merely raising the temperature of the metal to 100° C. Now WERTHEIM'S experiments seem at first sight to prove that the elasticity of iron and steel is greater at 100° C. than at the ordinary temperature of the room; but if M. WERTHEIM had examined the elasticity after the wire tested at the higher temperature had again cooled down to the lower one, he would have found that this *apparent temporary* increase of elasticity was *really a permanent* one, and if the wire had been tested several times, first at the higher and then at the lower temperature, he would have also found, provided sufficient rest after

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* All these experiments were repeated several times with different specimens of iron, but invariably with the same result as regards the nature of the change.

† Ann. de Chimie et de Phys., 3^{me} série, 1844.

cooling had been allowed, that the elasticity of both iron and steel is *temporarily diminished* by raising the temperature to 100° C.

From WERTHEIM'S researches* we gather that in the case of iron and steel there is the following increase of elasticity between 15° to 20° C. and 100° C.

TABLE XXIV.

Metal.	Increase per cent. of elasticity between 15° to 20° and 100° C.
Annealed iron	4·90
Annealed iron wire	6·91
Annealed cast steel	2·79
Annealed English steel wire . . .	23·20
Steel tempered blue	5·18

The increase of elasticity of the steel wire seemed so remarkable that it was determined to retry WERTHEIM'S experiments by direct observations of extension, using the same scale and vernier as have been already described in Part I., and placing the wire and the comparison-wire in the same air chamber as had been used in measuring the alteration of resistance produced by loading at different temperatures. The length of wire between the clamp, which rested on a wooden support on the top of the chamber, and the vernier was 4 feet 4 inches, and of this length 2 inches or rather more would be, roughly speaking, at the temperature of the room when the rest of the wire was heated by steam to 100° C. We must therefore multiply any observed effect on the elasticity caused by raising the temperature of the wire to 100° C. by a number which is about 4 per cent. of the apparent alteration. The air chamber rested (fig. 18) on a piece of wood, A A, 8 inches long, 6 inches broad, and ½ inch thick, and this in turn on two stout bricks, B B, which were supported by a wooden table, D D. The wire to be examined, X, and the comparison-wire, Y, were, as usual, secured at one end of each to the same clamp, C, which rested on a piece of hard wood, E E, placed at the top of the chamber. The wires, X and Y, passed through two small holes made in E E, and also through a hole in the table, and to their lower ends were attached, in the one case, a scale-pan, and in the other a cross-bar of wood, H H, carrying constant equal weights. Exactly the same precautions were taken as have been already fully described in Part I., and, as in experiments on the alteration of resistance produced by loading, the air chamber was well covered with baize and paper.

Under these circumstances it was possible to maintain a very constant temperature of 100° C., and even had the temperature varied slightly it will be seen that no appreciable error would have been introduced, as the variation would have altered the lengths of X and Y to the same extent.

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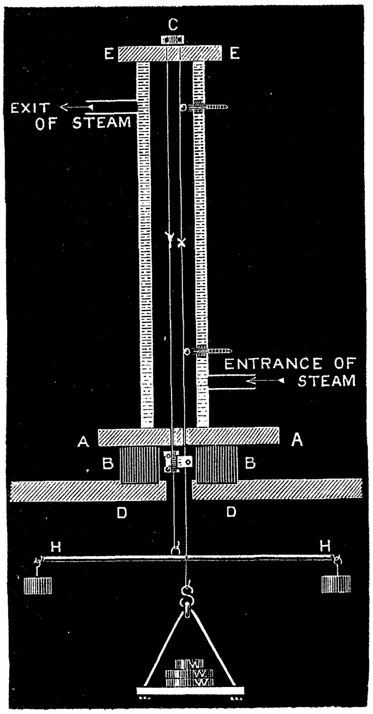
[*] Ann. de Chimie et de Phys., 3^{me} série, 1844, p. 431.

Fig. 18.



Experiment LV.

An annealed pianoforte-steel wire, ·085 centim. in diameter, was loaded for some hours with a weight of 10 kilogs.; this was then removed and a rest of 24 hours allowed, when a weight of 4 kilogs. was left permanently on the wire and the elasticity determined at the ordinary temperature of the room, and at 100° C., by putting on and taking off a load of 6 kilogs., the recovery being quite perfect for the load at both the higher and the lower temperatures.*

Number of trial.	Alteration of length produced by 6 kilogs. at 12° C. in half-millims.	Alteration of length produced by 6 kilogs. at 100° C.	Alteration of length produced by 6 kilogs. after cooling to 12° C.
1	1·48	1·49	1·45
2	1·50	1·49	1·46
3	1·51	1·50	1·44
4	1·51	1·48	1·44
5	1·51	1·48	1·46
6	..	1·48	..
Mean	1·502	1·487	1·450
Probable percentage of error . . .	·40	·27	·30

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* At the higher temperature after the *first* loading, which was not taken into consideration in estimating the elasticity.

Experiment LVI.

The same iron wire as had been used for Experiment LV. was loaded for some time with 8 kilogs. ; 4 kilogs. were then removed and the wire allowed to rest for 24 hours, when the effect on the length of the wire produced by putting on and taking off 2 kilogs. was found to amount to an alteration of ·940 half-millim. at 100° C. After the action of the steam had been stopped for two hours and the temperature was about 20° C., the alteration produced by the same load amounted to ·985 half-millim., and after 20 hours rest at the temperature of 13° C. was found to be ·945 half-millim. The wire was now tested with 4 kilogs., when the alteration of length produced by this new load was 1·910 half-millim. at 13° C., and after heating for some hours to 100° C., 1·911 half-millim. The source of heat having been removed and the wire allowed to cool slowly for 20 hours, the alteration caused by the same load was 1·880 half-millim. at 13° C.

Experiment LVII.

An annealed nickel wire, ·09213 centim. in diameter, was loaded for several hours with a weight of 18 kilogs.; 10 kilogs. were then permanently left on the wire for 24 hours, and the alteration of length effected by a load of 8 kilogs. at a temperature of 16° C. amounted to 1·250 half-millim. The wire was heated to 100° C., and the alteration was now found to amount to 1·360 half-millim. After cooling down for the next five hours to a temperature of about 20° C. the alteration became 1·350 half-millim., and after three days at a temperature of 15° C. proved to be 1·250 half-millim.

Experiment LVIII.

The same copper wire as had been used in Experiment XLIX. was loaded for some hours with a weight of 11 kilogs.; 7 kilogs. were then allowed to remain on permanently and the wire suffered to rest for two days. It was then raised to the temperature of 100° C. with the weight of 11 kilogs. on, and cooled again to the temperature of the room. These operations were repeated each four times during a space of four days, and on the last of these the alteration of length produced by a load of 4 kilogs. was found to be 1·374 half-millim. at 100° C. ; on cooling to 15° C. the alteration caused by the same load proved to be 1·310 half-millim., and this, or nearly the same alteration, had been found to be produced by the load at the temperature of the room, which temperature varied from 15° C. to 16° C. on each of the previous days.

The following table exhibits the difference of the alteration of electrical resistance and of length at the temperature of the room and at 100° C.

TABLE XXV.

Metal.	Percentage temporary alteration of elasticity caused by raising the temperature from 15° C. to 100° C. + signifies increase of elasticity produced by rise of temperature.		Percentage increase of alteration of resistance caused by raising the temperature from 15° C. to 100° C. − signifies decrease of alteration.
	WERTHEIM.	TOMLINSON.	
English steel wire . .	+23·20	−2·58	. .
Iron wire	+ 6·91	−1·64	+ 5·70
Copper.	− 6·59	−4·74	+ 1·87
Nickel	. .	−8·41	−50·00

Remarks on Experiments LV.–LVIII., and on Table XXV.

It appears from the last experiments that there is really a permanent increase of elasticity produced in annealed iron and steel by merely raising the temperature to 100° C.; and what is still more remarkable, there was in the case of one specimen of iron wire, which was so ductile as to lengthen by 24 per cent. before breaking,* such a large loss of ductility that its maximum permanent elongation *barely reached* 13 *per cent. after it had been heated to* 100° *C. and allowed to cool again.* As the last discovery was made when experimenting on the effect of permanent extension on the susceptibility of the resistance of iron to change of temperature, it was thought at first that the passage of the current used in determining the electrical resistance might have some influence on the ductility, but on heating three other pieces of the same wire to 100° C., and afterwards allowing them to cool without permitting any current to flow through them, almost exactly the same change was observed; and yet in all these cases the rate of cooling was slow; so much so, indeed, that with the last specimen employed, in which special precautions had been taken to surround the small air chamber in which the wire was heated with several coatings of baize, the chamber was sensibly warm to the touch 12 hours after the cooling had commenced. How far other kinds of annealed wrought-iron might show a change of ductility from like cause I know not, but it seems evident that changes comparatively enormous can be produced in the elasticity and ductility of this metal by small alterations of temperature.

It has also been shown by Experiment XXXIX. that the electrical conductivity of annealed steel is increased by heating slightly and then cooling quickly, and it will be proved in Parts III. and IV. that there is a correspondingly large effect on the magnetic inductive capacity and on the thermo-electric properties of steel produced by the same process. It would appear, therefore, that researches of this kind might lend valuable

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* This wire I received through the kindness of Mr. J. T. BOTTOMLEY, and was especially prepared for experiments on magnetic induction carried on in the physical laboratory of Sir W. THOMSON.

aid in investigations on the liability of wrought-iron axles to fracture produced by sudden changes of the temperature of the air.

Again, it will be observed from Experiment LVI. that shortly after the iron has been heated and then cooled there is less elasticity than when a considerable rest has been allowed; and in fact we have in this case exactly the same kind of restitution of elasticity in iron as we have seen takes place after the wire has experienced mechanical extension. With nickel the increase of elasticity produced by rest after cooling is still more remarkable. Equally remarkable also is the temporary change of elasticity produced in nickel; and a comparison of the loss of elasticity produced by raising the temperature to 100° C. with the change of susceptibility to alteration of resistance from change of stress as shown in Table XXIII. affords a still further proof that stress and strain act in the contrary direction as far as electrical conductivity is concerned.

It will also be noticed in Table XXV. that the alteration of susceptibility to change of electrical resistance from change of stress is greater in iron in proportion to the alteration of elasticity when the temperature is raised to 100° C., and that the converse is the case with copper, so that there is a greater or less alteration of *specific resistance* for the loaded wire than for the unloaded, caused by rise of temperature to 100° C., according as the metal is iron or copper; and we have seen that a similar state of things occurs where the strain is that left after the removal of the stress.

THE ALTERATION OF ELECTRICAL CONDUCTIVITY PRODUCED BY MAGNETIZATION.

History of the subject and description of apparatus.

This subject has, in the case of iron, received the attention of several observers, who have in some instances differed not only as regards the amount but also as regards the nature of the change produced by magnetization on the electrical resistance. Sir W. THOMSON, in 1856,[*] was I believe the first to show that magnetization affected the electrical conductivity of iron and steel, longitudinal magnetization causing in these metals increase, and transverse magnetization decrease of resistance, and this with steel was found to be the case whether the metal was hard or soft. Shortly afterwards experimenting on nickel, THOMSON found[†] with this metal also an alteration of resistance similar in kind to that of iron, but greater in amount for the same magnetizing force. With brass, on the contrary, he failed to detect any change whatever.

Subsequently BEETZ,[‡] CHWOLSON,[§] and myself[||] pursued similar investigations.

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[*] Phil. Trans., "Electrodynamic Qualities of Metals," Part IV.

[†] Proc. Roy. Soc., vol. viii., 1857.

[‡] POGG. Ann., vol. cxxviii., p. 202 (1866).

[§] CARL'S Rep., vol. xiii., p. 232 (1877).

[||] Proc. Roy. Soc., June 17, 1875, vol. xxiii., p. 533.

BEETZ and CHWOLSON both confirmed the results of THOMSON as far as longitudinal magnetization was concerned; but with the former of the two first observers an experiment where transverse magnetization was employed, ended in giving purely negative results. The values obtained in my own experiments differed considerably from those of THOMSON as regards amount and in the case of hard steel also in nature. Moreover, it appeared that the circular magnetization which ensues when a current is passing through an iron wire caused an increase of resistance, and as we might perhaps expect circular magnetization to cause a similar effect, as regards nature, on the conductivity to transverse magnetization,[*] these results were not in accordance with those of THOMSON. Unfortunately I had not at the time read Sir W. THOMSON'S paper, and investigations made in later years convinced me that the observations recorded in my "Preliminary Notice" were not reliable, partly because alteration of resistance from change of temperature had not been sufficiently guarded against, and partly because of a "PELTIER effect," which I have since found would, with the large battery-power employed in the circuit of the "WHEATSTONE'S bridge" arrangement, vitiate the results. To my astonishment, AUERBACH, three years afterwards, published an essay[†] "On the Passage of the Galvanic Current through Iron," in which my own observations both as regards the magnitude and nature of the changes produced in iron and hard and soft steel by longitudinal magnetization were apparently fully confirmed. Moreover, it appeared that he also agreed with me that circular magnetization caused increase of resistence in iron; and ingeniously reasoning that, this being the case, feeble longitudinal magnetization should decrease the resistance of iron, brought forward a series of experiments which seemed fully to bear out his views. Under these circumstances it seemed to be advisable to retry some of my old experiments on iron and steel *rods*, and further to extend the enquiry to *wires* of iron and steel.

As several of the instruments used in this part of the investigation have also been employed in several experiments yet to be described in the other parts of this paper, it seems advisable to give here some description of them, as well as certain data which will be required for converting the measurements taken into absolute units.

The tangent galvanometer.

This was of the usual HELMHOLTZ-GAUGAIN pattern, made by ELLIOTT Bros., where there are two stout copper rings for measuring currents where it is desirable that the resistance of the galvanometer should be small, and three pairs of coils of finer wire for other purposes. In these investigations the former only were employed, and therefore we may consider the resistance of the galvanometer itself to be neglectable.

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[*] This, however, is not, I believe, the case.

[†] Phil. Mag., July, 1879, vol. viii., p. 1. Translated from the original essay (Leipzig, 1878), communicated by the author.

The short needle was as usual provided with an aluminium index, and by means of this, readings on a graduated circle traversed by the ends of the index could be depended upon to within $\frac{2}{10}$ths of 1°. The needle was suspended by a platinum wire $\frac{1}{1000}$th of an inch in diameter and 12 inches in length, the upper end of the wire being secured to a torsion-head provided with a vernier, which moved over a graduated circle; by means of the vernier a torsion amounting to six minutes could be measured. The fine platinum wire hung in the axis of a brass tube which was provided near its lower extremity with a small glass window, so that the illuminated image of a vertical wire focussed by a lens could be received on a small mirror and reflected back on a scale placed at a distance of 1000 of its own divisions from the mirror. The mirror was attached to a piece of stout brass wire which was connected at its lower extremity with a needle, and at its upper extremity was clamped to the lower end of the platinum wire.

The effect of the torsion on the deflection was determined by a series of careful observations made by turning the torsion-head through different angles, first in one direction and then in the opposite, and noting the corresponding deflection of the needle. Thus, in one experiment, the torsion-head having been turned through 100 degrees from left to right, there was produced a deflection of 57° 6′, and when the head was turned from right to left, the deflection was 56° 46′ on the opposite side of the zero point; the mean of the two deflections of the needle is 57°, and therefore the force of 1° of torsion of the suspension wire would $=\frac{\text{sine } 57^\circ\times \text{H}}{(100-57)}=\cdot0195\times \text{H}$; where H is the horizontal force of the earth's magnetic action on the needle.

In order to be able to determine in absolute units the value of the deflections of the needle, a new Daniell's cell of large size was charged with a saturated solution of sulphate of copper and a semi-saturated solution of sulphate of zinc. This cell was allowed to rest for two hours after having been charged, and was then short-circuited for half an hour. After this time the cell was connected up with the thick copper wires of the galvanometer, and the deflection of the needle produced, observed by means of the mirror and scale, when external resistances of 0 ohm, 10 ohms and 20 ohms were successively introduced. The deflections were reversed in each case by reversing the battery-current and the mean values of the two deflections in the different directions were for 0 ohm, 324 divisions of the scale; for 10 ohms, 110 divisions; and for 20 ohms, 30 divisions; these deflections corresponding to 8° 59′, 3° 8′, and 0° 52′ respectively. By comparing the deflection with 0 ohm and 10 ohms in circuit, the internal resistance of the battery, together with the resistance of the connecting wires, was found to be 1·055 ohm, and by comparing the deflections with 10 ohms and 20 ohms in circuit, this same resistance was calculated to be 1·058 ohm; therefore, 1·057 ohm was assumed to be the true resistance. Again, taking the electromotive force of the Daniell thus charged to be 1·12 volt, or $1{\cdot}12\times10^8$ electromagnetic units, and the resistance of 1 ohm to be 10^9 of these units, the formula for converting the readings of the galvanometer into electromagnetic units was determined to be

$$\gamma = \cdot 3158\ (\tan\phi + \cdot 00839\phi \sec\phi),$$

where ϕ equals the deflection of the needle in degrees, and γ is the value of the current strength in absolute measure.

The magnetizing coils.

During a considerable part of these investigations two magnetizing coils were employed, of which descriptions are now given.

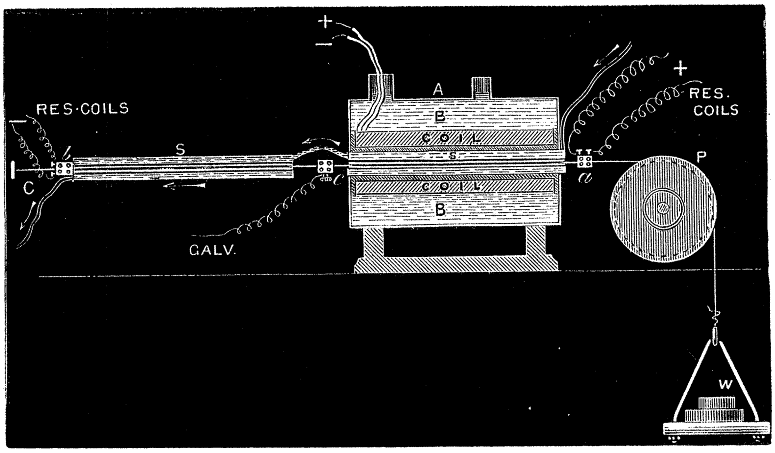
The larger of the two coils, which will be designated as the coil A, was made of about 1000 feet of cotton-covered copper wire, $\frac{1}{20}$th of an inch in diameter; the whole piece was divided into seven equal portions, and these, after having been well soaked in melted paraffin wax, were placed side by side and bound together by tape wound spirally along the whole length of the compound strand thus formed. This strand, after a further soaking in paraffin, was wound on a stout glass tube having an internal diameter of 1 inch and a length of 13 inches. The glass tube was provided at its two extremities with discs of hard wood $\frac{1}{4}$ inch thick and 6 inches in diameter, and surrounding the whole of the coil was a zinc cylinder concentric with the glass tube, which being closed at its two ends by discs of the same metal served when filled with water to keep the coil cool (fig. 19). The ends of each of the seven portions into which the whole wire was divided were connected with separate terminal screws so that the seven coils could be used either in "series" or in "multiple arc." When arranged in "series," in which form they were employed in this particular branch of the enquiry, the total resistance of the coils at 15° C. was 4·464 ohms. The compound strand was distributed along a length of 30 centims. in layers of five deep, so that the total number of turns amounted to 2100. The inner diameter of the coil was 3 centims. and the outer 7 centims.; therefore the magnetizing force at the centre and the two extremities would be respectively $4\pi \times c \times 70 \times \cdot 986$ and $4\pi \times c \times 70 \times \cdot 498$ absolute units, where c denotes the current strength, and the average force throughout the whole length would be $4\pi \times c \times 70 \times \cdot 742$.

The smaller of the two coils, the coil B, was constructed as follows:—A thin tube of polished brass, with a slit running throughout its entire length, $1\frac{1}{4}$ inch internal diameter and $4\frac{1}{2}$ inches long, was covered with vulcanised caoutchouc to a depth of $\frac{1}{16}$th of an inch, and on this was wound 3 lbs. of cotton-covered copper wire, $\frac{1}{20}$th of an inch in diameter, followed by 3 lbs. of wire, $\frac{1}{10}$th of an inch in diameter. Inside the first tube was placed a second of similar kind, 1 inch in internal diameter, and connected with rings of ebonite with the first at the two ends. The second tube was concentric with the first, and of the same length, so that between the inner tube and the outer there was interposed a layer of air nearly $\frac{1}{8}$th of an inch in thickness. This arrangement was employed to prevent the heat from the magnetizing coil reaching any wire or rod placed inside. The wire forming the coil had a resistance of 1·782 ohm at the temperature of 15° C., and was distributed in 814 turns in a length of 9·7 centims. The inner diameter of the coil was 3 centims. and the outer diameter 9·0 centims., so that the magnetizing force at the centre would be $4\pi\times c\times 90{\cdot}4\times{\cdot}851$, and that of the two extremities $4\pi\times c\times 90{\cdot}6\times{\cdot}478$ absolute units; consequently the average force throughout the coil would be $4\pi\times c\times 90{\cdot}4\times{\cdot}664$. As with coil A, the whole of the wire was well soaked in paraffin wax before winding, and the insulation between one layer and another was, by determining the resistance before and after winding, ascertained to be quite perfect in both A and B.

The Effect of Temporary Stress on the Alteration of Electrical Resistance produced by Magnetism.*

In order to test the effect of temporary and permanent extension on the change of electrical resistance produced in iron wire by magnetism, the following arrangement was adopted:—The wire, which had a total length of from 4 to 5 feet, was firmly secured at one end (fig. 19, C) to a strong upright, and was then slipped through two glass tubes of small diameter about 13 inches in length; the glass tubes were placed inside two copper vessels, S S, of the same length as themselves. These vessels each consisted of two concentric cylinders connected by soldering at the two extremities by copper rings and provided with small pipes, so that cold water could be kept running through the space between the cylinders. The outer of the cylinders was 1 inch nearly in external diameter, and the inner ¼ inch in diameter; one of the copper vessels was placed inside the magnetizing coil, A, whilst the other was supported on the table.

Fig. 19.



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* It should be mentioned here that in all these experiments the magnetizing coils were placed in a direction *perpendicular to the magnetic meridian.*

The wire passed over a large wooden pulley, P, and to the other end of it was attached a scale-pan for holding weights. The light clamps *a*, *b*, *c*, having been well secured to the wire, were connected up in the usual manner, as shown in the figure, with the galvanometer, battery and resistance-coils, the connecting wires in this case being for a distance of 2 feet of rather fine silk-covered copper, in order to avoid the strain which would probably have ensued from the comparatively heavy caoutchouc-covered wires ordinarily employed. The whole arrangement was then carefully covered over with baize, and water allowed to trickle from a small cistern through S, S for about an hour, the space B having been previously filled with water. After a sufficient time had elapsed to render the parts of the wire of the same temperature, the effects on the resistance of magnetism alone or magnetism combined with strain were determined. The tangent galvanometer was placed in the circuit of the coil A* for the purpose of measuring the current passing through the coil.

Experiment LIX.

An annealed iron wire, ·093 centim. in diameter. B.C. produced by one Leclanché. M.C.† by 10 Grove cells with adjustable resistances in the external part of the circuit.

Number of kilogs. on the wire, scale-pan weighing 2 kilogs. not included.	Tangent of deflection galvanometer = tan α.	Alteration of resistance in terms of the platinum-silver wire $= d$; one division = an alteration of ·00081 per cent.	$\frac{d}{\tan \alpha}$.
0	·123	48·6	395
0	·249	65·0	261
8	·249	40·0	. .
0	·105	40·0	381
4	·105	27·0	. .
6	·105	22·0	. .

Experiment LX.

Another piece of the same wire was loaded and unloaded several times with a weight of 12 kilogs., and was afterwards allowed to rest for several days unloaded. The changes of resistance were then determined by noting the position of the light on the scale, the B.C. being produced by a large Daniell's cell, the circuit of which, as well as that of the galvanometer, was kept closed as soon as the balance had been

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* In the figure the manner in which the compound strand of the coil is arranged in "series" is not shown.

† The current in the circuit of the "Wheatstone's bridge" will be denoted by B.C. and that in the magnetizing circuit by M.C.

established. The effect of magnetization on the resistance was tested when loads of 0, 6, 10, and 12 kilogs. were on the wire. The M.C. was produced by five GROVE cells.

Tangent of the deflection of the needle of the tangent galvanometer.	Load in kilogs. on the wire when under magnetization, the scale pan weighing 2 kilogs. not included.	Alteration of resistance produced by magnetization in divisions of the galvanometer-scale; one division representing an alteration of ·0005 per cent.
. .	0	27
·247	6	19
. .	10	25
. .	12	25

Both these experiments show that the increase of resistance which was produced by the longitudinal magnetization is lessened by temporary stress up to a certain limit of the latter, and several other experiments of a similar kind proved that after the diminution of alteration of resistance caused by magnetization had reached a maximum, further temporary stress began to reverse the first effect, sometimes only just before the "breaking-load" of the wire had been reached. In no case, however, was *diminution* of resistance caused by longitudinal magnetization for the highest stress which could be put upon the wire without breaking it,* and this, too, when strengths of current of very different degrees were tried.

Experiment LXI.

An annealed nickel wire, ·105 centim. in diameter, was arranged in the same manner as the iron wire in the last experiment; but the clamps *a* and *c* (fig. 19) were placed nearer together, and just inside the coil A, so that the whole of the nickel experimented on would be under the influence of the magnetizing force. In this case the coolers, S S, were dispensed with, and, instead, the wire to be tested was provided with a solenoid of fine silk-covered copper wire, wound in two layers on a glass tube of the same length as that of the nickel wire under examination, and of a diameter such that the latter could be easily slipped inside it. This solenoid served, when required, to give the relative amounts of magnetism imparted to the steel by the different magnetizing forces. The alterations of resistance produced by the magnetism were first determined, then the galvanometer having been disconnected from the "bridge" and joined up with the solenoid, the induced currents caused by the magnetization were measured by the

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* This was rather unexpected; since JOULE has shown (Phil. Mag., 1847, vol. xxx., pp. 76, 225) that whilst iron free from stress is increased in length by longitudinal magnetization, yet when loaded beyond a certain limit its length is diminished by the same cause.

"throw" of the needle, both with and without the B.C. flowing through the nickel. A preliminary set of observations had given the means of determining the amount of current which would be induced when the nickel was not in the coil, and, therefore, by subtraction the induced currents due to the nickel only could be determined. The glass tube and the fine silk-covered copper wire on it would have served to shield the nickel from any change of temperature likely to be caused by the magnetizing current; but as a further precaution, the solenoid was well wrapped up in paper so that it would just fit inside the coil A. The comparison-wire was also surrounded with glass and caoutchouc tubing, and, as with the iron, the whole arrangement was well covered over with baize.

The following values (Table XXVI.) of the alterations of resistance are the means of five or six trials with each of the various magnetizing forces employed.

Table XXVI.

M.C. in divisions of the scale of the tangent galvanometer α.	Throw of the galvanometer needle due to induction current caused by magnetization of the nickel when the load on the wire = 0 kilog. β.	Increase of resistance in terms of division of the platino-iridium wire when the load on the wire = 0 kilog. γ.	$\frac{\gamma}{\alpha}$.	$\frac{\gamma}{\beta}$.	Increase of resistance calculated from the formula $\gamma = a.\alpha + b.\beta$ $a = {\cdot}2992$ $b = {\cdot}1514$.	Increase of resistance caused by magnetism with 2 kilogs. on the wire.	Increase of resistance caused by magnetism with 6 kilogs. on the wire.	Increase of resistance caused by magnetism after the removal of the 6 kilogs. and after a rest of two days.
19	8·7	7·0	·368	·805	7·00	6·0	2·0	8·6
35	16·2	12·4	·354	·765	12·92	. .	. .	. .
53	25·6	19·1	·360	·746	19·73	. .	. .	. .
69	31·0	24·6	·356	·781	25·30	24·5	19·8	33·1
86	36·8	31·3	·364	·851	31·30	. .	. .	. .
159	56·4	57·0	·358	1·011	56·10	53·0	45·0	80·0
279	81·5	95·8	·343	1·175	95·80	99·1	85·2	131·0

It is evident from the last experiment that the increase of resistance which can be produced by magnetizing nickel wire longitudinally is diminished by temporary longitudinal stress not carried beyond a certain limit, provided the magnetizing force does not exceed a certain critical value depending upon the amount of stress applied. Thus we see that when the value of α is somewhere between 159 and 279, the load of 2 kilogs. begins to increase the alteration of resistance caused by the magnetization. Now, Sir W. THOMSON has proved*—and in the case of this particular wire I have been able to verify the fact†—that with nickel the magnetism induced by any magnetizing force is increased or diminished by stress according as the magnetizing force does or does not exceed a certain critical value. With iron, on the contrary, the induced

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* "Electrodynamic Qualities of Metals"—Part VII., Phil. Trans., Part I., 1879.

† I shall have occasion to refer to this experiment in Part III. of my paper.

magnetism is increased by stress, provided the magnetizing force does not reach a certain critical value, which however is very much less, other circumstances being the same, than is the case with nickel. It is possible, therefore, that if much smaller magnetizing forces had been employed in Experiment LIX., the increase of resistance caused by magnetism would be found to be heightened by the loads employed in that experiment.

THE EFFECTS OF PERMANENT LONGITUDINAL EXTENSION OF TORSION AND OF TEMPERING ON THE ALTERATION OF ELECTRICAL RESISTANCE PRODUCED BY MAGNETIZING.

The last experiment shows that moderate permanent logitudinal strain largely increases in the case of nickel the susceptibility to alteration of resistance from longitudinal magnetization. A similar effect is produced on iron, but as the whole point will be more fully discussed in Part III., it will suffice here to state that several experiments made according to the above plan, and also others where the comparison-wire and the wire to be tested were placed together in the magnetizing coil, proved, undoubtedly, that moderate permanent strain *increases* the susceptibility, but that this increase, after reaching a maximum, begins to decline, so that in some cases after the wire had been broken by the stress applied, the susceptibility appeared to be less than it was before the wire had been subjected to any strain. The above-mentioned maximum point depends upon the amount of magnetizing force in a manner to be hereafter described.

The effect of permanent torsion up to a certain point was to *diminish* the susceptibility to alteration of resistance from longitudinal magnetization, and the amount of diminution was independent of the direction either of the M.C. or the B.C.

The following experiment shows that in hard steel longitudinal magnetization increases the electrical resistance.

Experiment LXII.

A piece of a steel knitting-needle, 7·62 centims. in length and ·23 centim. in diameter, was hardened by heating it to a bright red and then plunging it into cold water. The piece was connected up with another of similar dimensions and similarly prepared, and both having been well covered with caoutchouc and silk, were made to form two branches of a "WHEATSTONE'S bridge." The coil B was used to impart magnetism, and with a large LECLANCHÉ for the B.C., and four GROVE'S cells for the M.C., an *increase* of resistance represented by 30 divisions of the iridio-platinum wire was obtained. The brass clamps used to connect the pieces of steel with each other, and with the other branches of the "bridge," were so massive that even in this case their resistance is neglectable; and since 30 divisions of the iridio-platinum wire would show an alteration of resistance of ·010 per cent., we may assume that this last number represents approximately the extent to which the conductivity of the steel was diminished by the longitudinal magnetization.

Moreover, the steel under examination was well within the coil, the comparison-piece being, of course, outside, and also at right angles to the coil; and it was calculated that the increase per unit of resistance would for unit magnetizing force be $\frac{\cdot 00010 \times 9\cdot 7}{814 \times \cdot 68 \times 4\,\pi \times c} = 69\cdot 8 \times 10^{8}$, since c, the strength of the magnetizing current here, approximately amounted to ·2 absolute unit.

It will be observed, by comparing this last result with the corresponding one in Experiment LXVIII., that the alteration of resistance produced by a given magnetizing force is very much less with the hardened steel than that caused by the same magnetizing force in a steel rod of the same diameter, but in the same condition as it was when received from the makers. Several other trials were made with the same piece of steel, in which smaller and smaller amounts of M.C. were employed, but in no case could any alteration of the nature of a *decrease* of resistance be observed.

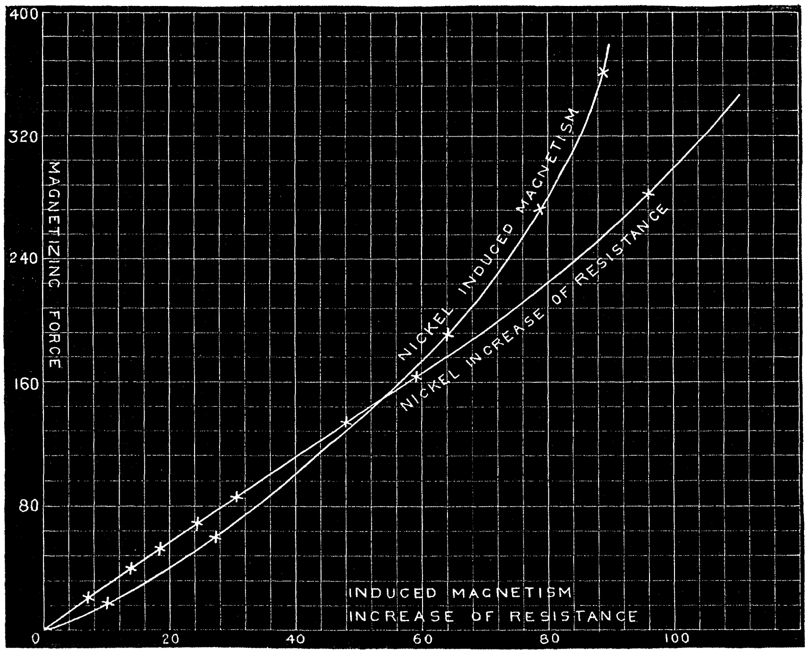
A similar experiment had been tried with pianoforte steel wire, hardened in the same way, and with various amounts of M.C., but the results were of the same nature, though much less in amount, as with the knitting-needle. It may be added that both the knitting-needle and the wire were made so hard that they were quite brittle, and with both there was a permanent as well as a temporary increase of resistance produced by the magnetization.

AN ATTEMPT TO DETERMINE RELATIONS BETWEEN THE ALTERATION OF ELECTRICAL RESISTANCE PRODUCED BY ANY MAGNETIZING FORCE, THE FORCE ITSELF, AND THE MAGNETISM INDUCED BY THE FORCE.

On consulting the fourth, fifth, and sixth columns of Table XXVI., it will be observed that the increase of resistance ensuing from magnetization depends not only upon the magnetism induced, but also upon the magnetizing force itself; and, in fact, we may say that if γ denotes the increase of resistance, whilst α and β represent the magnetizing forces and the magnetism induced respectively, $\gamma = a.\alpha + b.\beta$, where a, b are two constants. In the case of the nickel wire, α and β were measured in terms of the divisions of the scale of the tangent galvanometer, and of the scale of the THOMSON'S reflecting galvanometer respectively; whilst a and b were calculated from the observations made with $\alpha = 279$ and $\alpha = 86$. The agreement between the observed and calculated values of γ is good, and certainly quite equal to that between the different observations made with the same values of α. Columns 4 and 5 show clearly that the alteration of resistance depends in this case more on the value of the magnetizing force than on the magnetism induced, and from the fact that $\frac{\gamma}{\alpha}$ is nearly constant throughout, whereas $\frac{\gamma}{\beta}$ rapidly increases for the higher values of α, we are led to infer that the alteration of resistance would go on increasing as the magnetizing force increased, even when there might be no appreciable advance in the value of the magnetism induced.

A glance at the curves in Table XXVII. will serve to confirm the above view. These curves have their abscissæ representing both the induced magnetism and the alterations of resistance produced by the various magnetizing forces, which latter are measured by the ordinates of the curves. The induced magnetism* is represented on a scale of 1 millim. to one division of the scale of the THOMSON'S reflecting galvanometer, and the alteration of resistance on a scale of 1 millim. to one division of the platino-iridium wire. The ordinates are on a scale of 1 millim. to two divisions of the scale of the tangent galvanometer, and each of these latter divisions represents a current of ·00023 absolute unit. Each division of the iridio-platinum wire represents an alteration of resistance =·000034 per unit; if therefore we take the average of the first six values of $\frac{\gamma}{\alpha}$, namely, ·360, as representing the average alteration of resistance effected by a magnetizing current producing a deflection of one division on the scale of the tangent galvanometer, we find that the increase of resistance per unit produced in the nickel wire by unit magnetizing force $=\frac{\cdot 36 \times \cdot 000034 \times 30}{\cdot 00023 \times 2100 \times \cdot 75 \times 4\pi}=8070 \times 10^{-8}$.

TABLE XXVII.—Curves showing the increase of resistance and the amount of induced magnetism produced in nickel wire by different magnetizing forces.



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* There was no appreciable difference between the induced magnetism as determined with the B.C. flowing and that without.

Experiment LXIII.

An annealed iron wire, ·094 centim. in diameter, was arranged with the same precautions and in the same manner as the nickel wire in the last experiment; but as it was found difficult to make observations in the ordinary way in consequence of the VILLARI's "shock-currents" being very pronounced, the B.C., for which one GROVE's cell was employed, was kept flowing until the wire and the comparison-wire had assumed a sufficiently stable resistance-ratio which was very nearly equal to unity. The alteration of resistance produced by various magnetizing forces was measured by the deflection of the image of the illuminated wire on the scale, and the mode of taking the readings and the nature of the corrections to be applied for the direct action of the magnetizing coil on the galvanometer are described in Experiments LXIX. and LXXI.

The following table contains the results of this experiment:—

TABLE XXVIII.

M.C. in divisions of the scale of the tangent galvanometer. α.	Throw of the galvanometer needle due to the induction current caused by the magnetization of the iron. B.C. flowing. β.	Throw of the galvanometer needle due to the induction current caused by the magnetization of the iron. B.C. not flowing. β'.	Increase of resistance in terms of divisions of the galvanometer scale. γ.	$\frac{\gamma}{\alpha}$.	$\frac{\gamma}{\beta}$.	$\frac{\beta}{\beta'}$.	Increase of resistance calculated from the formula $\gamma = a.\alpha + b.\beta$ $a = ·0397$ $b = ·106$.
21	20	17	1·9	·091	·095	1·18	2·9
43	56	42	5·0	·116	·090	1·33	7·7
82	107	71	13·1	·160	1·220	1·51	14·6
130	134	91	19·3	·148	1·440	1·47	19·4
203	153	103	23·9	·118	1·562	1·49	23·9
383	200	. .	36·9	·096	1·845	. .	36·4
519	220	172	43·9	·085	2·000	1·28	43·9

Table XXVIII. shows that with iron as with nickel the increase of resistance can be represented by the formula $\gamma = a.\alpha + b.\beta$,* and, here again therefore, it seems as if the alteration of resistance would go on increasing as the magnetizing force increased even when there would be no perceptible increase of induced magnetism. The cases of iron and nickel, however, differ considerably in one respect, namely, that whereas with the latter metal the magnetizing force played the more important part in altering the

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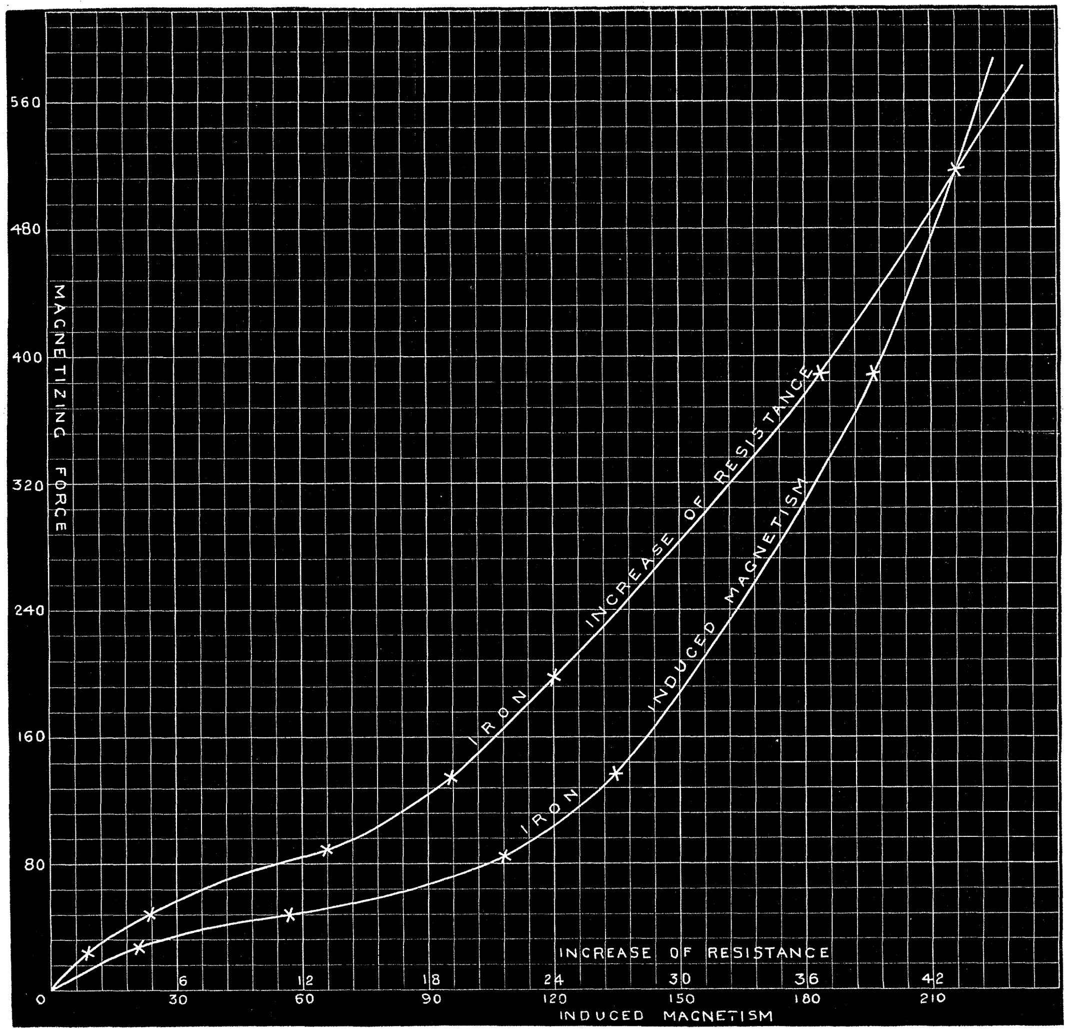
* The discrepancies between the observed and calculated values of γ for the first three magnetizing forces is, I believe, almost if not entirely due to the fact that, unfortunately, before any exact measurements had been made with the lower values of α, the full magnetizing force had been employed. This would not perhaps have affected the result, as far as the agreement between observation and calculation is concerned, had the induced magnetism been measured at the same time as the alteration of resistance, but this was not the case.

resistance, with the former, for moderate values of the M.C. the greater part of the alteration is effected by the induced magnetism.

Table XXIX.—Curves showing the increase of resistance and the amount of induced magnetism produced in iron wire by different magnetizing forces.



The curves in Table XXIX. showing the amount of magnetism induced and of the alteration of resistance are constructed on the same lines as those in Table XXVIII., except that in consequence of the alteration of resistance being much less and the induced magnetism greater with iron than with nickel, the alteration is represented on a scale of 1 millim. to ·3 division of the scale and the induced magnetism on a scale of 1 millim. to $1\frac{1}{2}$ divisions of the scale. Each division of the scale represents an alteration of resistance amounting to ·000023 per unit, and if we take the mean of the third and fourth values[*] of $\frac{\gamma}{\alpha}$, which may perhaps be assumed to represent approximately the average alteration of resistance for a given moderate magnetizing force, we find that with this wire the increase per unit of resistance produced by an absolute electromagnetic unit of magnetizing force would be 2335×10^{-8}.

It is desirable to draw attention also to the fact that with both iron and nickel there is no change of resistance of the nature of a *decrease* produced by magnetization, but that starting with a current from one GROVE'S cell through a total external resistance of about 15 ohms[†] and with a magnetizing force not greater than 26 times the earth's horizontal magnetic force at the place, we find a continuous *increase* of resistance as the magnetizing force is increased.

THE EFFECT OF ALTERING THE STRENGTH OF THE B.C. ON THE CHANGE OF RESISTANCE PRODUCED BY ANY MAGNETIZING FORCE.

The results recorded in the last two experiments are so far at variance with AUERBACH'S views already alluded to, that it seemed advisable to still further test these views by altering the strength of the B.C. whilst that of the M.C. is maintained constant.

Experiment LXIV.

A piece of the same annealed nickel wire as that used in Experiment LXI. was tested with one GROVE'S cell and a total external resistance of 15 ohms for the M.C., and with from one to three GROVE'S cells with no external resistance save that offered by the "bridge" and its connexions for the B.C.

Deflection of the needle of the tangent galvanometer, showing the strength of the B.C.	Increase of resistance caused by the magnetization in terms of the divisions of the iridio-platinum wire.
12°	10·1
15	10·3
17½	10·9

The numbers given in the second column are the means of several observations, and agree very fairly with each other, the difference between them being within the errors of observation, and what difference there is would show that we have a slightly *greater* increase of resistance for large values of the B.C. than for small ones.

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[*] The first two values of $\frac{\gamma}{\alpha}$ are not included, for the reason previously mentioned.

[†] That is, 10 ohms in addition to the resistance of the coil and its connecting wires.

Experiment LXV.

A piece of the same iron as had been used in Experiment LXII. was tested with one Grove's cell and no external resistance save that of the magnetizing coil for the M.C., and three Grove's cells with adjustable external resistance for the B.C.

B.C. in terms of the divisions of the scale of the tangent galvanometer.	Increase per unit of resistance. M.C. = 109 divisions of the scale of the tangent galvanometer.
130	·000300
940	·000316
1521	·000353

In this experiment, which was conducted in the same manner as Experiment LXII., there is evidently a *greater* alteration produced by magnetism when the B.C. has a high value than when it has a low one, and the differences between the different values in the second column are certainly larger than could be attributed to errors of observation. Now in Experiment LXVIII. it will be shown that with unannealed steel, and in Experiment LXI. it has been shown with annealed nickel, that there is little or no difference in the amount of alteration of resistance effected by magnetism when the B.C. is made to vary in amount; and the reason is apparent, for with the nickel and the steel there was no* appreciable difference between the induced currents caused by the magnetization of these metals when the B.C. was flowing and when it was not, whereas, if we turn to the second, third, and seventh columns of Table XXVIII., we see that there is a very appreciable difference in the case of the annealed iron wire, between the induced currents with and without the B.C.

All these experiments are in direct contradiction to those of Auerbach, but yet it was thought fit to try others with annealed pianoforte-steel wire.

Experiment LXVI.

A piece of annealed pianoforte-steel wire, 10 centims. long and ·085 centim. in diameter, was tested with various battery-power from one to four Grove's cells for the B.C., and battery-power varying from one Grove's cell with a resistance of 10 ohms in the external circuit besides the resistance of the coil A, to seven Grove's cells with no external resistance save that of A for the M.C.

In no case was a *diminution* of resistance produced by magnetization. With one Grove's cell for the B.C., and seven Grove's cells for the M.C., an increase of resistance of ·0585 per cent. was observed: lower values of the M.C. gave smaller and smaller results as the M.C. diminished. The alteration of resistance produced by unit magnetizing force was estimated in the usual manner to be 1500×10^{-8} per unit.

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* That is, no difference of such an amount as to make it seem worth while at the time to record it.

Experiment LXVII.

A strand of four pieces of the same length and of the same steel as that used in the last experiment was tested with one GROVE's cell in the B.C., and seven in the M.C., and the alteration of resistance, which, however, could not be accurately measured, was certainly not *greater* than that of the single wire when the same battery-power was employed for both the M.C. and the B.C. The change of resistance of the compound strand under the above-mentioned conditions was measured at ·040 per cent. with a probable error of 25 per cent.

THE EFFECT OF LONGITUDINAL MAGNETIZATION ON THE ELECTRICAL RESISTANCE OF A BAR OF STEEL.

As my earliest investigations recorded in the previously-mentioned "Preliminary Notice" had seemed to show that the alteration of the electrical resistance of iron and steel which can be produced by magnetization is very much greater, for the same amount of magnetizing force, when the metals are in the form of comparatively thick rods than in that of wires, the following experiment was made.

Experiment LXVIII.

A steel knitting-needle, taken in the ordinary condition, 23 centims. in length and ·233 centim. in diameter, was provided with two copper terminals, 14 centims. in length and ·410 centim. in diameter, holes having been bored 1½ centim. in depth at one end of each terminal so as to admit the ends of the needle. A similar and similarly-furnished needle served as the comparison-piece, and the two were connected with each other and with the other parts of the "bridge" in the same manner as the wires in the last experiments had been. The clamps used, however, were more massive and the whole of the steel to be magnetized was well within the coil A, whilst the comparison-piece was outside the coil and at right angles to it. The amount of magnetism induced was measured as before, but the resistance introduced into the circuit of the galvanometer employed for this purpose had to be made very considerably greater than was the case with the iron wire, in order that the "throw" of the needle might be reduced to the proper extent. The B.C. was produced by four GROVE's cells, and the M.C. by seven GROVE's cells, each with adjustable external resistance. The following are the results obtained :—

TABLE XXX.

M.C. in divisions of the scale of the tangent galvanometer $=\alpha$.	"Throw" of the galvanometer needle due to induction current by magnetization of the steel $=\beta$.	Increase of resistance when B.C.=19½° of tangent galvanometer, the increase measured in divisions of platino-iridium wire.	Increase of resistance when B.C.=29°.	Increase of resistance when B.C.=38°.	Mean increase of resistance $=\gamma$.	Increase of resistance calculated from formula $\gamma'=\cdot 0386\times\alpha+\cdot 0588\times\beta$.	$\frac{\beta}{\alpha}$.	$\frac{\gamma}{\beta}$.
23	7	1·35	. .	. .	1·35	1·30	·31	·193
108	32	6·48	. .	. .	6·48	6·05	·30	·203
152	48	8·83	8·50	8·75	8·69	8·69	·32	·181
267	82	. .	15·00	. .	15·00	15·13	·31	·183
347	102	18·88	20·30	19·00	19·39	19·39	·30	·190

From this experiment we learn that the magnetism induced in the steel is, for the magnetizing forces employed, very nearly proportional to these latter, and also that the alteration of resistance is nearly proportional to the induced magnetism, and therefore to the magnetizing force. Still more closely can the alteration of resistance be calculated from the formula $y=a.\alpha+b.\beta$, where the constants a and b, given as ·0386 and ·0588, are determined from the alterations of resistance caused by values of the M.C. equal to 347 and 152 divisions of the scale of the tangent galvanometer.

Alteration of the strength of the B.C. seems to have little or no influence on the change of resistance produced by a given amount of magnetizing force, and therefore we may assume that the product of the mean values of $\frac{\beta}{\alpha}$ and $\frac{\gamma}{\beta}$ will fairly represent the alteration which would be wrought by a current in the magnetizing coil which would suffice to deflect the needle of the tangent galvanometer through one division of the scale.

This product $=\cdot 0589$, and since a division of the iridio-platinum wire corresponds to an increase per unit of the resistance of the steel $=\cdot 000032$,* and, since also one division of the scale of the tangent galvanometer represents a current of ·00023, whilst the average magnetizing force due to unit current would in the present instance be $\frac{2100\times\cdot 82\times 4\pi}{30}$, we see that the maximum increase of resistance obtained by the magnetization was ·062 per cent., and that the increase of resistance per unit for unit magnetizing force would be 1137×10^{-8}.

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* Of course correction is here, and in all similar cases, made for the resistance of the terminals, which, however, with these rods was very small.

THE EFFECT OF LONGITUDINAL MAGNETIZATION ON THE ELECTRICAL RESISTANCE OF A BAR OF NICKEL.

Experiment LXIX.

A bar of nickel, 8·3 centims. long and ·70 centim. in diameter, was soldered to two stout copper terminals, whilst a similar bar, similarly provided, served as a comparison piece. The bars were arranged in the same manner as the steel bars in the last experiment, but the magnetizing coil B was used instead of A. Before placing the nickel in B it was covered with several layers of stout caoutchouc, and the comparison piece having been furnished in like manner, the usual precautions of well covering both bars were taken. The B.C. was furnished by two GROVE'S cells and the M.C. by eight GROVE'S cells with adjustable external resistance. The circuit of the B.C. was kept closed, and the alteration caused by magnetization in the resistance of the bar was measured by the deflection of the image of the illuminated wire on the scale.*

As the resistances to be compared are in this case very small, it is advisable to show how far any measurements of alteration of resistance can be depended upon, and for this purpose the first set of readings with the smallest M.C. are given :—

Total deflection caused by passing the M.C. in terms of divisions of the galvanometer-scale. + signifies increase of resistance.†	Number of trial.
+8·50	1
+8·25	2
+7·00	3
+6·25	4
+7·75	5
+8·50	6
+8·00	7
+9·00	8
+8·25	9
+7·75	10
+7·25	11
+7·9	Mean.

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* In this, and in every other instance in which such a mode of measuring alteration of resistance was adopted, the direct action of the magnetizing coil and of the included metal core on the galvanometer when the latter was not in circuit was always determined by a separate set of experiments, as though such action was small, it could never be entirely avoided. The distance (several yards) of the coil from the galvanometer was however such that no perceptible difference in the sensibility of the latter was introduced when the M.C. was closed. Similar remarks apply to the tangent galvanometer, and the readings given are in the case of both instruments always corrected for the above mentioned direct action. For the mode of taking the readings see Experiment LXXI. on Bismuth.

† Each number is calculated from three consecutive readings in the manner described in Experiment LXXI.

The deflection due to direct action of the electromagnetic solenoid and included core when the galvanometer was disconnected from the "bridge" $= +2{\cdot}9$.

Therefore the deflection due to alteration of resistance $= +5{\cdot}0$.

Immediately after taking the above readings the effect of altering by ·1 ohm the side of the "bridge" adjacent to the side containing the bar was found to be a deflection of 190 divisions on the scale, and since the ratio of the resistance of the bar and its copper terminals to that of the comparison piece was $\frac{12{\cdot}2}{10{\cdot}0}$, it was assumed that the increase of resistance amounted to $\frac{5{\cdot}0 \times {\cdot}1}{190 \times 12{\cdot}2}$ per unit. The deflection of the needle of the tangent galvanometer was in this case 4°, and a similar set of observations was made when the M.C. produced deflections of 6·25°, 8·25°, 10·75°, and 13°, with the results recorded below.

TABLE XXXI.

Deflection of tangent galvanometer $= \phi$.	$\tan \phi + {\cdot}0084\phi \sec \phi = c$.	Increase of resistance due to magnetization in terms of divisions of the galvanometer scale $= \alpha$.	$\frac{}{c}$.	$\frac{\alpha}{c^2}$.
$\overset{\circ}{4{\cdot}00}$ 6·25 8·25 10·75 13·00	·104 ·163 ·215 ·284 ·343	5·0 9·8 17·0 24·0 32·5	48·1 60·1 79·1 84·5 94·4	462 369 368 298 275

It would seem that the increase of resistance produced by the magnetization varies in this case more nearly as c^2 than as c; if, however, we take the mean value of the numbers for $\frac{\alpha}{c}$ we shall probably obtain a sufficiently close approximation to what can only be regarded as a rough measurement of the effect of magnetization on the resistance. This mean value is 73·2. The resistance of the nickel only was to that of the nickel and the connexions in the ratio of 3·8 to 12·2, and since the value of c must be multiplied by ·316 in order to obtain the value of the current in C.G.S. units, and since moreover a unit current would produce an average magnetizing force in this case of $\frac{814}{9{\cdot}7} \times {\cdot}7 \times 4\pi$, we see that the increase per unit of magnetizing force would on the whole be $\frac{73{\cdot}2 \times {\cdot}1 \times 9{\cdot}7}{{\cdot}316 \times 3{\cdot}8 \times 190 \times 814 \times {\cdot}7 \times 4\pi}$, or 4343×10^{-8}. The bar was cast, and used in the same state as sent by the makers;* when annealed the value given above would be considerably greater, as it was afterwards ascertained that annealing very largely increased the capacity for induction from moderate magnetizing forces.

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* For this bar and for the bars of cobalt and bismuth used in the next experiments I am indebted to Messrs. JOHNSON, MATTHEY, and Co. All the bars here mentioned were very nearly chemically pure.

THE EFFECT OF LONGITUDINAL MAGNETIZATION ON THE ELECTRICAL RESISTANCE OF A BAR OF COBALT.

Experiment LXX.

A bar of cobalt, 8·5 centims. long and ·75 centim. in diameter, was provided with stout copper terminals, and balanced against a similar bar. The precautions taken and the mode of experimenting were exactly the same as with the nickel bar.

TABLE XXXII.

Deflection of tangent galvanometer $=\phi$.	Tan ϕ + ·0084ϕ sec ϕ $=c$.	Increase of resistance due to magnetization in terms of divisions of galvanometer scale $=a$.	$\frac{a}{c}$.	$\frac{a}{c^2}$.
4·00°	·104	1·40	13·5	130
6·25	·163	3·90	24·0	147
13·00	·343	8·50	24·8	72

In this case the values of $\frac{a}{c}$ agree quite as well as $\frac{a}{c^2}$, and if we take the mean of the former, namely 21·1, we obtain an increase of resistance per unit attending magnetization by a unit force $=628\times10^{-8}$; a number, it will be noticed, only about one-seventh of that obtained in the case of the nickel. The cobalt was, like the nickel, unannealed, and annealing would have caused the effect of a moderate magnetizing force to be greater, though not so much greater as would be the case with nickel.

In both the nickel and cobalt bars there was a *permanent* increase of resistance produced by magnetization, the maximum alteration amounting in nickel to about ·125 per cent., and in cobalt to ·025 per cent.; so that the maximum permanent alteration of resistance which is caused by magnetization is much greater with nickel than cobalt.

With both bars the M.C. was found to produce very nearly the same alteration of resistance, whether passed in one direction or the other through the coil.

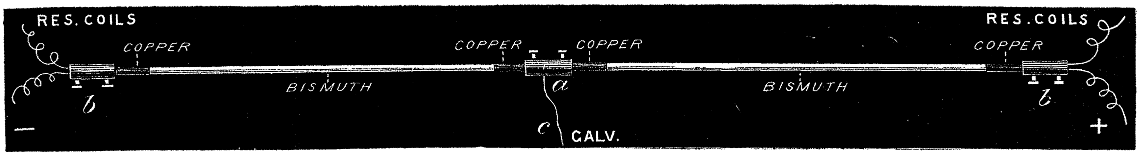
THE EFFECT OF LONGITUDINAL MAGNETIZATION ON THE ELECTRICAL RESISTANCE OF A BAR OF BISMUTH.

Experiment LXXI.

As it seemed desirable to ascertain whether diamagnetic substances would have their resistances altered in the same direction as paramagnetic ones, some experiments were made with bars of bismuth, but as the magnetization which can be imparted by an electromagnetic solenoid to bismuth is very much smaller than is the case with iron, nickel, or cobalt, it is proper that rather fuller details should be given in describing the results obtained so that the trustworthiness of these results may be duly estimated.

A bar of bismuth, 25 centims. in length and ·330 centim. in diameter, was provided with copper terminals of the same diameter, and connected up with a similar bar to the "bridge," as shown in fig. 20. In this figure the relative dimensions of the bismuth bars and their copper terminals, as well as the mode of establishing the "bridge," are sufficiently shown. To the binding screw, *a*, a silk-covered copper wire, *c*, was soldered to connect the bars with the galvanometer, whilst the two binding screws, *b b*, were provided with silk-covered copper wires leading to the poles of one Grove's cell and to two resistance coils of 100 ohms each in the usual manner. The coil A was employed, and the bars were arranged in the same manner and with the same precautions as the iron wire used in Experiment LIX., except that now it was necessary to dispense with the glass tubes in order that the bismuth bars could be slipped into the copper vessels through which the water flowed. The bars were, however, well varnished and covered with tissue-paper so as to ensure thorough insulation. The B.C. was kept closed and the alteration of resistance observed in the same manner as with the nickel and cobalt bars. The M.C. was produced by 13 Grove's cells, and the deflection of the needle of the tangent galvanometer was 22·5°. The readings given below are determined in each case as usual from three consecutive readings; thus, *a b c* being three consecutive readings the recorded number is $\frac{a+c+2b}{4}$.

Fig. 20.



Number of trial.	Deflection of galvanometer-needle in scale divisions. + signifies apparent increase of resistance on magnetization.
1	10·00+
2	10·00+
3	9·50+
4	10·25+
5	11·00+
6	10·50+
7	10·25+
8	10·75+
Mean	10·23+

The B.C. was now taken off and the direct action of the magnetizing coil on the galvanometer was found to produce a deflection of 8·00+. Therefore there seemed to be an increase of resistance caused by magnetization represented by 2·23 scale divisions. The B.C. was again put on, and by taking out and putting in ·1 ohm several times it was ascertained that this caused a movement of the image of the wire through 74·0 divisions. Moreover, when the M.C. was flowing, putting in or taking out ·1 ohm caused the same effect, and therefore the M.C. did not affect the sensibility of the galvanometer. In this case ·1 represented an alteration of resistance amounting to ·001 per unit, and therefore the increase of resistance from magnetization would be $\frac{2{\cdot}23 \times {\cdot}001}{74}$ per unit $= {\cdot}000031$ per unit and ·0031 per cent.

The B.C. was now reversed and the following observations taken :—

Number of trial.	Deflection of galvanometer-needle in scale-divisions. + signifies apparent increase. − signifies apparent decrease.
1	7·50−
2	8·00−
3	8·00−
4	7·75−
5	7·75−
6	8·25−
Mean	7·88−

The B.C. was again taken off and the direct action of the coil on the galvanometer appeared to be now 9·5−.* Here, therefore, there would be an increase of resistance equal to that represented by 1·62 scale divisions, and the amount of increase would be ·0022 per cent. Again, the resistances of 100 ohms on two sides of the bridge were replaced by 10 ohms, so that now the arrangement having become more sensitive, a set of observations similar to the above gave an increase of resistance equal to 3·88 divisions of the scale, corresponding to an increase of ·0029 per cent. From the three sets of observations it was concluded that the electrical resistance of bismuth is *increased* by longitudinal magnetization by ·0027 per cent. for the amount of magnetizing force here employed. The increase per unit of resistance for a unit magnetizing force would be 21×10^{-8}.

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* For some reason the direct action of the magnetizing coil on the galvanometer was never quite the same for both directions of the M.C.

THE EFFECT OF LONGITUDINAL MAGNETIZATION ON THE ELECTRICAL RESISTANCE OF ZINC FOIL.

Experiment LXXII.

A piece of commercial zinc foil, 14 inches in length and ·040 millim. in thickness, was wrapped lengthwise round a soft iron bar of circular section, $\frac{1}{2}$ inch in diameter and 15 inches in length, which had previously been coated with two layers of brown paper. The width of the foil was such that when wound round the bar the edges just overlapped. The foil was secured in position by fine yet strong twine, and having been covered with two folds of brown paper the whole was placed centrally in the coil A. At the two ends the foil was cut so as to allow of these ends being clamped in the usual manner in brass blocks, and a strip of foil of similar dimensions served as the comparison-piece. The same mode of experimenting and the same precautions were taken as with the bismuth bar. Seven GROVE's cells were used for the M.C., and these produced a deflection of 15° of the needle of the tangent galvanometer. Several trials which accorded very fairly with each other showed a mean *increase* of resistance represented by 3·8 divisions of the scale. The M.C. was reversed, and again several trials showed an increase of resistance, the mean value of which was represented by 3·5 divisions. From the data obtained it was calculated that the increase of resistance amounted to ·0148 per cent. The iron core having been removed no appreciable change in the resistance of the zinc foil could be detected on passing the M.C.

THE EFFECT OF LONGITUDINAL MAGNETIZATION ON THE ELECTRICAL RESISTANCE OF COPPER WIRE.

Experiment LXXIII.

A piece of silk-covered copper wire, 12 feet in length and $\frac{1}{50}$th of an inch in diameter, was doubled backwards and forwards so as to form a bundle 1 foot in length. The whole was then well coated with shellac varnish, and when dry inserted into one of the copper coolers (fig. 19), which was placed in the coil A. A similar bundle served as the comparison-piece, and the two bundles were connected up in the usual manner with the bridge. One GROVE's cell was used for the B.C., and the deflection of the tangent galvanometer produced by the M.C. was 16°. The B.C. was kept on for 10 minutes, and whilst still on the following readings were taken:—

Number of trial.	Apparent alteration of resistance caused by magnetization. – signifies apparent decrease of resistance.
1	6·0 –
2	4·5 –
3	6·5 –
4	6·5 –
5	6·5 –
6	7·0 –
7	7·0 –
8	6·5 –
9	7·5 –
Mean	6·44–

The B.C. was now taken off, and the direct action of the coil on the galvanometer was found to be 6·50. There would therefore, on the whole, appear to be an *increase* of resistance of 0·6. The B.C. was again put on, and a similar set of observations to the above produced when the the M.C. was reversed, an apparent increase of 7·80 divisions; whilst the direct action of the coil on the galvanometer caused a deflection of 8·00 in the same direction, so that now, on the whole, there would appear to be a *decrease* of resistance represented by ·20 division of the scale. The mean result of the two sets of observations would give a decrease of resistance represented by ·07 division of the scale. Now, in this case, the galvanometer had been made so sensitive by proper use of the adjusting magnet that an alteration of ·1 ohm on one of the two sides of the bridge, containing each 100 ohms, caused a deflection of 300 divisions of the scale; accordingly 1 division of the scale would represent an alteration of resistance amounting to $\frac{1}{300000}$ per unit, and ·07 an alteration of *less than one in four millions*. It is needless to say that this experiment shows that there is no reliable change of resistance to be detected even with the comparatively large magnetizing force employed in this case—a force which would be more than 480 times that of the earth's magnetic horizontal force at the place. The copper in this case was the ordinary copper wire usually employed for electrical purposes, but other experiments were made with chemically pure copper, and these all yielded results quite as negative as those just recorded. There is no doubt that the electrical resistance of copper is altered by magnetization; but in order to detect such alteration we should, in all probability, require the aid of a very powerful electromagnet* and a galvanometer in a very sensitive condition. Such change of resistance must be exceedingly small even with the most powerful magnetizing force that we can at the present time bring to bear—much smaller than would seem to

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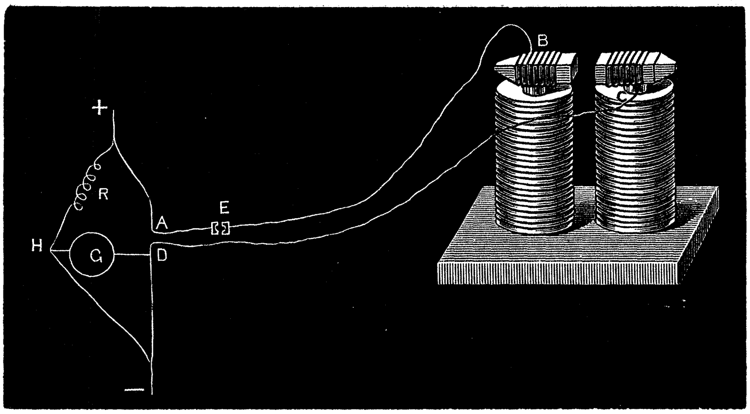
* One might, perhaps, by adopting the same plan as that used with the zinc foil, succeed in obtaining evidence of alteration of resistance in the case of copper foil.

follow from Stewart and Schuster's experiments, some of the details of which will now be discussed.

Discussion of Stewart's and Schuster's Experiments on the Alteration of the Electrical Resistance of Copper by Magnetization.*

Stewart and Schuster, in a preliminary notice, bring forward the results of certain experiments which in their opinion seemed to prove that the electrical resistance of copper wire is altered by magnetization; but a glance at their mode of operating serves to show that the effects observed by them cannot be relied upon. In fig. 21 (copied from Phil. Mag., 1874) A B C D is a caoutchouc-covered copper wire several yards in length wound round the armatures of an electromagnet, and R is another resistance against which the copper wire is approximately balanced. The alteration of resistance was observed from the "*throw*" of the needle of the galvanometer G, caused by closing the B.C. by means of the contact-breaker E, first when the electromagnet was actuated by six Grove's cells and then without any current in the M.C., or *vice-versâ*. The galvanometer was in such a position with reference to the electromagnet that the latter produced very little direct effect on the former, and since they obtained *momentarily* an increase of potential at D compared with the potential at H when the M.C. was passing, they inferred that the magnetization imparted by the electromagnet to the wire decreased the resistance of the copper.

Fig. 21.



These experimenters, however, seem to have entirely overlooked the fact that the powerful magnetization imparted by the magnet to the armatures would alter the capability of the latter to receive fresh magnetism. Now, when the B.C. is closed at E, the current in the coil of wire wrapped round the armatures would induce magnetism in the latter, and this would in turn send an *induced current through the caoutchouc-covered wire in the opposite direction to that of the original;* if, then, the capability of

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* Phil. Mag., May, 1874.

receiving fresh magnetism is *lessened* in the armatures by previous powerful magnetization this induced current would be *lessened*, and thus, if their mode of experimenting was adopted, the resistance of the wire would *seem* to be decreased. The following experiment was tried with a view of testing the effect of previous magnetization on the capability of receiving fresh magnetism in the case of the armature of an electromagnet.

Experiment LXXIV.

A bar of soft iron, 12 inches long $\frac{1}{2}$ inch broad and $\frac{1}{2}$ inch thick, was placed across the cores of a small electromagnet, and separated from them by a piece of tissue paper. The cores of the electromagnet were 1 inch in diameter and 5 inches in length, and were wound round with the cotton-covered copper wire $\frac{1}{16}$th of an inch in diameter, and having a resistance of nearly 1 ohm. A battery of six GROVE'S cells was employed with the electromagnet, and in order to test the change of susceptibility to magnetization, some 200 turns of rather fine silk-covered copper wire were made round one end of the bar of soft iron and distributed over a length of 4 inches. The coil thus formed was connected with the galvanometer, and was further insulated from the iron core by two layers of paper. The coil was then placed inside the coil B, which itself could be placed in the circuit of one large DANIELL'S cell by means of a mercury-cup. The current induced by the magnetization imparted by the coil B to the soft iron bar was measured by the "throw" of the galvanometer-needle produced when the circuit of the DANIELL'S cell was closed, first without exciting the electromagnet and then with this magnet in action. The electromagnet was at such a distance from the galvanometer that no error of importance caused by the direct action of the former would be introduced. The following experiments were then made :—

Condition of electromagnet. "On" signifies magnet excited; "off" not excited.	Deflection of the image of the illuminated wire on the scale.	Difference effected in the deflection by the action of the electromagnet. + signifies increase, – signifies decrease produced by exciting the electromagnet.	Number of trial.
Off	227	. .	1
	226	. .	2
	227	. .	3
On	270	43+	1
	223	. .	2
	186	41–	3
	186	. .	4
	186	. .	5
Off	212	26–	1
	202	16–	2
	202	. .	3
On	233	31+	1
	187	15–	2
	187	. .	3
Off	212	25–	1
	200	. .	2
	198	11–	3
	198	. .	4

The current through the electromagnet was then reversed.

Condition of electromagnet.	Deflection of the image of the wire.	Difference effected in the deflection by the action of the electromagnet.	Number of trial.
On	198	. .	1
	192	. .	2
	192	. .	3
Off	250	58–	1
	212	20–	2
	212	20–	3
On	204	8–	1
	202	10–	2
	202	10–	3

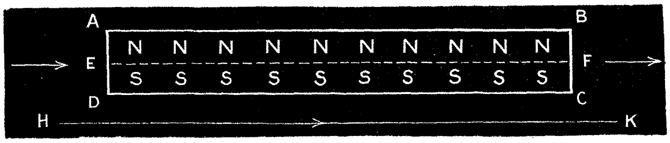
It will be noticed that for both directions of the M.C. the induced current is less with the electromagnet excited than when not.

Several phenomena connected with the experiments in the paper above alluded to can be explained by referring the apparent alteration of resistance to the permanent, sub-permanent, or temporary alteration of the magnetic susceptibility of the soft iron armatures employed; and, on the whole, when we consider that, as stated by them, the electromagnet had no apparent effect to make a piece of the wire set either axially or equatorially, we must regard their results with great suspicion.[*]

I myself seven years ago tried the effect of an electromagnet on a copper wire coiled several times round a flat piece of hard wood, and placed between the poles of a powerful electromagnet actuated by 12 GROVE's cells, but in no case could I detect the slightest real alteration of resistance. The galvanometer then employed was only able to detect an alteration of 1 in 50,000 of the resistance, and I look forward with some interest to renewed experiments in the same direction with the much more sensitive instrument which I have at present.

THE EFFECT OF ANNULAR MAGNETIZATION ON ELECTRICAL RESISTANCE.

Fig. 22.



Let A B C D, fig. 22, be a thin slice of iron (in the plane of the paper), through which an electric current is passing in the direction of the arrows. The molecules at the upper part, A B, will tend to take up positions such that their axes are perpendicular to the plane of the paper and with their north ends above it. The magnetization imparted to the molecules will diminish from A B to the axis E F, where it will be zero, and below this axis the molecules will be impelled to place their south poles above the plane of the paper. If now H K be an independent current passing below A B C D, it will tend to reverse the magnetism of the molecules at C D and strengthen that of the molecules at A B; but since the lower molecules are nearer to H K than the upper ones, the total effect would be a partial diminution of the annular magnetism imparted by the current flowing through A B C D. If, on the contrary, the current below the wire flows from K to H, the annular magnetism would on the whole be increased.

Now, some years ago, when making attempts to discover whether the resistance of an iron wire could be altered by passing a current above or below the wire, I was led to believe that such was the case. Among several other experiments, a knitting-needle provided with copper terminals was placed upon a strip of copper 16 inches long, 3 inches broad, and $\frac{1}{20}$th of an inch thick; the strip was well varnished, and the needle was laid upon it in such a position that the axis of the needle was

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[*] It seemed to be the more desirable to test these results, as AUERBACH twice alludes to them in his paper (Phil. Mag., July, 1879, pp. 15–17), and should they not be correct, as I cannot help feeling is probably the case, others might be misled, owing to the well-deserved reputation of these experimenters.

coincident in direction with a line drawn from end to end of the strip and bisecting the two ends. On passing a current through the strip the resistance of the wire was altered in such a manner as would make it appear that circular magnetization *decreased* the resistance. I cannot, however, place reliance on these experiments, which at the time seemed conclusive, as I have in my recent attempts not been able to verify their results when sufficient precaution was taken to avoid change of resistance from change of temperature. The following are two experiments made with the above-mentioned object:—

Experiment LXXV.

An annealed iron wire, 4 feet in length and ·085 centim. in diameter, was firmly bound by tape for a distance of 2 feet with a caoutchouc-covered copper wire $\frac{1}{16}$th of an inch in thickness. The two parts of the wire were arranged as usual to form two sides of a "WHEATSTONE's bridge"; and whilst the B.C. was varied in different trials to very different extents and the current through the copper wire was increased from almost 0° to 50° of the tangent galvanometer, *no trace whatever* could in any case be detected of alteration of the resistance of the wire by passing a current through the copper wire, though the arrangement was sufficiently delicate at times to show an alteration of *one in one million.* At one time, indeed, it was suspected that there was an alteration, but this was afterwards traced to a slight direct action of the M.C. on the galvanometer.

Experiment LXXVI.

A strip of annealed iron foil, 8 inches in length 2 inches broad and $\frac{1}{30}$th of an inch thick, was placed upon a copper strip 12 inches long 3 inches broad and $\frac{1}{10}$th of an inch thick, the two being separated from each other by two folds of a silk handkerchief. Another strip of iron of similar dimensions served as a comparison piece, and the two iron strips were arranged as usual in the "bridge." Though the currents through the strips of both iron and copper were altered to the same extent as with the iron wire, there was still no trace of alteration of resistance caused by the current in the copper strip. It is hardly necessary to say that such arrangements as these are not favourable for bringing out the effect sought, inasmuch as the distances of the copper wire and copper strip conveying the current were both greater than the thickness of the iron itself;* but, on the other hand, if we make the iron thicker we diminish the sensitiveness of the arrangement, and we certainly cannot well diminish the distance of the copper from the iron without laying ourselves open to error from changes of resistance caused by heating.

Several attempts were now made to ascertain whether variation of the B.C. itself

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* With the wire twice as great and with the strip nearly equal.

would cause any variation in the resistance of iron wire, of which the next experiment will furnish a sample.

Experiment LXXVII.

An annealed iron wire, 14 inches long and ·85 millim. in diameter, was balanced against a platinum wire $\frac{1}{30}$th of an inch in diameter, and of nearly equal resistance. The B.C. was varied by interposing different amounts of resistance in the external circuit of one GROVE'S cell, and this could be done very quickly by a suitable arrangement of mercury cups. Resistance coils of 10 ohms each were used in the two branches of the bridge, where 100 ohms resistances were generally employed.* As it was found impossible to allow the current to flow for even two or three seconds without unduly heating the wire, and as VILLARI'S "shock-currents" would cause the resistance of the iron to appear greater than it should be when the B.C. was closed, and less than it should be when the B.C. was opened, the following plan was adopted :—The B.C. was, at intervals of 30 seconds, closed and *immediately* afterwards opened; and in this way it was found possible to obtain the value of the resistance-ratio of the iron and platinum so nearly, that on moving the sliding-piece to points on the iridio-platinum wire 20 millims. above or below the supposed balancing-point, a deflection of several divisions could be obtained in one direction or the other. As the contrary "shock-currents" produced by closing and immediately opening the B.C. would not quite neutralise each other's impulsive effects on the galvanometer-needle, it is obvious that the effects on the galvanometer, due simply to the fact of the sliding-piece being equal distances above or below the true balancing-point, would not produce equal deflections, but that, by taking the mean of these deflections, the true point might by easy calculation be determined. As a sample of the mode of experimenting we will take the following case :—The true balancing-point *seemed* to be 55 millims. to the right of the zero of the iridio-platinum wire, and 3 ohms were at this time in the circuit of the B.C. ; on moving the sliding-piece to 75 a deflection, on closing and immediately afterwards opening the B.C., of five divisions to the left was obtained (a left deflection would here indicate that the sliding-piece should be moved to the left in order to get the true balance). The sliding-piece was now moved to 35, and a deflection of six divisions to the right was obtained on closing and opening the B.C. From this we learn that the true balancing-point would be $35+\frac{6\times 40}{11}=57$ nearly. The resistance of 3 ohms was then removed, and similar observations gave 58 as the balancing-point. Immediately afterwards, the 3 ohms resistance having been again introduced, the point appeared to be 56. The true balancing-point when 3 ohms were in was therefore assumed to be $\frac{57+56}{2}$, and when

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* It may be perhaps as well to state here that when small resistances were being compared, 10 ohms instead of 100 ohms were generally employed, though this fact has not been always mentioned.

the 3 ohms were removed to be 58. In this way the following results were arrived at as the means of several trials :—

Resistance in the external circuit of B.C.	Position of equilibrium of the sliding-piece.	Number proportional to the B.C.
10	56·7	1·0
3	55·8	2·8
0	55·7	11·0

Now when we bear in mind that one division of the iridio-platinum wire only represents an alteration of resistance of ·0033 per cent., it appears evident that alteration of the strength of the B.C. can have but very small effect on the resistance, and even if there is any alteration it is of such a nature as to show that circular magnetization produces *decrease*, not increase of resistance.

Discussion of Auerbach's Experiments.*

The results recorded in the last few experiments are so completely at variance with my own former observations,† and with those of Auerbach that it is very desirable to attempt to account for the discrepancies. I cannot help thinking that Auerbach experimenting, as it would seem, in almost precisely the same manner as I did in 1875, may have been misled in the same way as I now believe myself to have been. We both employed copper terminals to our iron wires whose resistances were in some cases even greater than that of the wire itself, and therefore necessarily not very thick, and moreover balanced this compound wire of copper and iron against a wire of German-silver. Now when a current is passing through a wire compounded of two metals placed end to end, a "Peltier effect" is produced such that an electromotive force is developed which sends a current in the opposite direction to the original; so that, if we attempt to find the resistance of the compound wire in the usual manner by closing the battery circuit and shortly afterwards that of the galvanometer, we shall obtain an apparent value for the resistance which will depend upon the battery-power employed, upon the length of time that the battery circuit has been closed, upon the medium surrounding the wire,‡ and upon the thermo-electric power of the two metals forming the compound wire whose resistance we wish to determine. Nor is the "Peltier effect" necessarily confined to the two junctions, for since no wire can be made perfectly homogeneous

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* Phil. Mag., July, 1879.

† Ibid., June, 1875.

‡ That is whether this medium tends to preserve the inequality of temperature at the two junctions or not.

throughout, there must be unequal heating wherever two dissimilar parts of the wire join, and therefore consequently there must be developed at each such junction an opposing electromotive force. Indeed, may not the large resistance of such alloys as German-silver and platinum-silver be in a great measure due to a similar unequal heating at the junctions of the molecules of the several metals forming the alloy: with this difference, however, that here there would be an equalization of temperature the rapidity of which would be more and more approached in the case of a compound circuit made up of several pieces, say of iron and copper, as the distances between the consecutive junctions of these pieces became less and less?

Further, besides the error likely to arise from the "PELTIER effect," we must expect to encounter another, inasmuch as the heat generated in a wire by the passage of a current by no means necessarily produces the same alteration of potential at the two junctions. This may be from two causes: either different rises of temperature may be produced because the terminal at one end carries off more heat than that at the other, or because the metals which appear to be identical at the two junctions are not so.

That the "PELTIER effect" does come largely into play sometimes, we can convince ourselves by passing a current from a single cell of DANIELL for five or ten seconds through a thermopile, and then, after disconnecting the cell from the pile, putting the latter in circuit of a galvanometer; in such case a very considerable deflection can be obtained with a delicate instrument, and, indeed, we can even make the warmth of the hand, pressed against the face of one thermopile, generate such a "PELTIER effect" in a second pile connected with the first, that on disconnecting the two from each other, and then connecting the second with a reflecting galvanometer, a deflection may be obtained which can be rendered visible at a considerable distance. The following experiments will show that such errors as those above-mentioned are by no means merely theoretical.

Experiment LXXVIII.

A silk-covered German-silver wire, $\frac{1}{30}$th of an inch in diameter, was soldered at its two extremities to two copper terminals, $\frac{1}{16}$th of an inch in diameter and 6 inches in length, the whole forming a fairly accurate resistance coil of half an ohm. The coil was put for 20 seconds in the circuit of one GROVE'S cell, and then, after the cell had been disconnected, and when a further period of five seconds had elapsed, connected by a mercury cup with a galvanometer; a deflection of 200 divisions was obtained, whereas, previously, there had been no perceptible deflection. After a rest of five minutes there was only a deflection of some 20 divisions. The battery was now reversed, and after a connexion with the coil for 20 seconds, a deflection of 170 divisions was obtained in the opposite direction.

Experiment LXXIX.

A piece of annealed iron wire with copper terminals, both of similar dimensions to those of the wire and terminals in the last experiment, was treated in the same manner as the German-silver, and deflections of 50 and 25 divisions, both on the same side, were obtained. The wire and its terminals were in this case well wrapped up in paper, and, as in the previous experiment, there was no sensible deflection before the GROVE's cell was used. These experiments, which are only two out of several which were made with different pairs of metals, show that with the German-silver the electromotive force generated by the "PELTIER effect" was so far greater than that due to any other cause that the deflections were nearly the same on both sides; whereas with the iron the current produced by the unequal heating of the two junctions from other causes than the "PELTIER effect" predominated, and this was found to be the case with several specimens of iron and copper.

In my experiments of 1875 I balanced iron wires or iron rods against wires of other materials, and using rather powerful electromotors (from one to six GROVE's cells) proved, as I thought, that the electrical resistance of iron increases with the intensity of the current employed in the "bridge;" but in these later investigations, in which, having a much more delicate galvanometer, I could obtain a measure of the resistance of the substance within 1 in 50,000 with a battery-power one-tenth of the smallest then used, I have been unable to detect with certainty any such change.

As for the discrepancies which exist between my present and former observations on both soft iron and hard steel, I can only attribute them to errors caused by the magnetizing coil being too close to the iron or steel to allow of sufficient protection from errors caused by heat radiated or conducted from the former, and which might increase the resistance of the metal as a whole, or cause apparent increase or decrease by unequal change of potential at the junctions of the two copper terminals with the iron or steel. At any rate, using both steel and iron of the same qualities as used then, but adopting more perfect thermal insulation and a more accurate mode of experimenting, I have been unable to detect any such considerable increase of resistance in the case of soft iron or soft steel, or any decrease of resistance of hard steel, as I did then. Now AUERBACH, with some of his specimens of iron and steel wires, obtained apparent alterations of resistance of 1, 2 and even 3 per cent.—alterations of decrease or increase which would have, in the case of specimens of a similar nature used by myself, sent the reflected image of the illuminated wire flying off the scale, whereas, instead of this, I found nothing but variations of resistance which never, with wires of a similar diameter, reached even to ·1 per cent., and this, too, with magnetizing forces which must have equalled those employed by AUERBACH.

AUERBACH, again,* seems to concur with BEETZ and others that the mere mechanical pull connected with magnetizing would have caused an apparent decrease of resistance

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* *Loc. cit.*, p. 151.

in THOMSON'S experiment on the effect of transverse magnetization on the electrical resistance of iron;* but when one considers the small effect of even a far larger stress than could have been produced by magnetization on the electrical resistance of iron, as shown in Table I., these objections must, I think, vanish; and further, with nickel whose resistance THOMSON has proved to be altered similarly to iron,† the effect of mechanical stress is of *an opposite* nature to that produced by magnetization.

REMARKS ON THE NATURE OF THE ALTERATION OF RESISTANCE WHICH IS PRODUCED BY MAGNETIZATION.

It will be observed in Table XXXIII., in which are given the values of the increase of resistance produced by unit magnetizing force, that of all the metals examined annealed nickel is the most affected,‡ and that next in order come soft iron, soft steel, cobalt, and bismuth. Evidently the condition of the metal may largely affect the susceptibility to alteration of resistance, and from what we have previously learned the thickness may do so also, but in a direction opposite to that which was at first expected, namely, that thick wires would be less affected than thin ones when the same B.C. and M.C. were employed.

TABLE XXXIII.

Name of metals.	Condition.	Diameter in millimetres.	Increase of resistance per unit. produced by unit magnetizing force.
Iron	Annealed . . .	0·94	2335×10^{-8}
Steel	Annealed . . .	0·85	1500×10^{-8}
Steel	Unannealed . .	2·33	1137×10^{-8}
Steel	Very hard . .	2·33	70×10^{-8}
Nickel	Annealed . . .	1·05	8070×10^{-8}
Nickel	Unannealed . .	7·00	4343×10^{-8}
Cobalt	Unannealed . .	7·50	628×10^{-8}
Bismuth	Unannealed . .	3·30	21×10^{-8}

Had the nature of the change of resistance been the same for mechanical longitudinal stress as for longitudinal magnetization in the case of *all* metals, there is nothing in the actual *amount* of alteration that might not lead us to suppose that the change of resistance from the latter cause is due to mere rotation of the molecules, as molecules, without regard to the electric currents, which, according to AMPÈRE'S hypothesis, are constantly circulating round these molecules. But when we find that with nickel

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* Phil. Trans., 1856, p. 741.

† Proc. Roy. Soc., vol. viii., 1857.

‡ It is remarkable that the value of the "rotational coefficient" of nickel should also exceed that of the other magnetic metals.

longitudinal mechanical stress, which must cause rotation of the molecules to a certain extent, but without magnetic polarity, actually, unless carried to a very great excess, produces decrease of resistance, we are probably right in conjecturing that the change of resistance resulting from magnetization is in a great measure due to the fact that the current used in the "bridge" is encountered by a set of molecular currents circulating all more or less in the same direction, and in planes more or less at right angles to the direction of the former current as the induced magnetism is greater or less.

RELATION BETWEEN THE "ROTATIONAL COEFFICIENT" OF METALS AND THE ALTERATION OF RESISTANCE PRODUCED BY MECHANICAL STRESS.

E. H. HALL has discovered that when a strip of metal along which a current is passing is placed between the poles of an electromagnet in such a position that the lines of magnetic force are perpendicular to the plane of the strip, an electromotive force is developed in a direction at right angles both to the plane of the strip and the lines of force, and that thus the current is deflected. This deflection varies in amount and also in direction with different substances, and Professor HALL has recently read before the British Association a paper[*] on this subject, in which he gives a table showing the extent and direction of the deflection produced in several metals. The extent of the deflection in any substance depends among other things upon a certain constant designated by Professor HALL as the "rotational coefficient." In this table the sign + or — is prefixed to the number representing the coefficient according as the current is deflected in the same direction in which the conductor itself tends to move, or the opposite. Below is given HALL's table, and appended to it the numbers representing the increase of specific resistance per unit temporary increase of length when this latter is produced by mechanical stress. A + sign prefixed to the numbers denotes an increase, and a — sign a decrease of specific resistance.

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[*] 'Nature,' Nov. 10, 1881. (Abstract of a note on the above subject read by Professor E. H. HALL at the meeting of the British Association at York.)

TABLE XXXIV.

Name of metal.	"Rotational coefficient."	Temporary alteration of specific resistance per unit produced by temporary increase of length per unit. + signifies increase of resistance on application of stress.
Iron	+ 78	+2·618
Zinc	+ 15	+2·113
Lead	..	+1·613
Tin	+ 0·2	+1·630
Brass	− 1·3	..
Platinum	− 2·4	+2·239
Silver	− 8·6	+1·617
Copper	− 10·0	+1·005
Aluminium	− 50·0	−0·420
Nickel	−120·0	−8·860

Considering that HALL himself is doubtful about the order of the metals in the centre of the list, there seems to be a well-marked relation between the "rotational coefficient" and the alteration of specific resistance from temporary mechanical stress. This relationship is strikingly apparent in the case of the metals iron, zinc, copper, aluminium, and nickel, and there can be but little doubt that results of extreme interest might be obtained by observations of the effect of mechanical stress and strain on the "rotational coefficient."

THE RELATION BETWEEN ELECTRICAL RESISTANCE AND "VISCOSITY."

Whilst endeavouring to find a relation between the electrical resistances of substances and their other physical properties, I was struck with the failure which I experienced in finding any in the case of those properties which have been already examined, except one, and that is one which as yet I have not had time to examine with anything like the care which I hope at some future period to be able to bestow upon it, namely, that which has been called by Sir W. THOMSON, in the case of metals, their "viscosity." The experiments, however, which have been made show clearly that there is in all probability a very close relationship between molecular friction and electrical resistance. It is proposed to make extended observations of the diminution of amplitude of vibration of wires of considerable length whilst the oscillations of very small amplitudes are magnified by a mirror attached to the vibrator; so that small vibratory molecular displacement may be obtained, and further to examine the change of "viscosity" produced by change of temperature. It suffices, however, for the present to say that of the pure metals already examined, copper, silver, aluminium, zinc, and tin, the order of their "viscosity" is the same as that of their specific electrical resistance.

SUMMARY OF PART II.

1. The electrical resistances of iron, steel, platinum, German-silver, copper, platinum-silver, brass, zinc, silver, aluminium, tin, lead, and carbon are temporarily increased by temporary longitudinal stress, the amount of increase being nearly, but not quite, proportional to the stress.

2. The *specific* electrical resistances of all the above metals, except aluminium, is likewise temporarily increased by temporary longitudinal stress; with aluminium, however, the specific resistance is *decreased.* The total resistance and the specific resistance of nickel are both *decreased* by temporary longitudinal stress not exceeding a certain limit, whilst beyond this limit further increase of stress begins to produce increase of resistance. The alterations, both increase and decrease, are very considerably greater with this metal than those of any of the other substances examined.

3. The temporary alteration of specific resistance caused by stress is much less with the alloys German-silver, platinum-silver, and brass than with the several components of these alloys; this would suggest an apparent relation between the change of resistance caused by alteration of temperature and that due to mechanical stress; the former effect, however, is very much greater than the latter, if we regard the alterations of resistance attending the same amount of expansion in each case, and there is no doubt that the increase of resistance ensuing on rise of temperature is due almost entirely to other causes than mere expansion.

4. The elasticity of carbon rods varies considerably with different specimens, even from the same maker, and is nearly proportional in this case to the eighth power of the density. Thick rods have generally a less density than thin ones, and less elasticity.

5. The specific resistance of carbon also varies considerably with different specimens from the same maker, but there is no apparent relationship between specific resistance and elasticity.

6. The increase of resistance caused by longitudinal stress is with different specimens of carbon as with different specimens of other substances very nearly proportional to the amount of temporary elongation produced by the stress, and though with the exception of tin and lead, the total alteration of resistance resulting from a given amount of stress is less with the metals which have been examined than with carbon, this is not so with regard to the alteration of specific resistance.

7. Compression produces on the electrical resistance of substances an effect of a contrary nature to extension.

8. Stress applied in a direction transverse to that of the current produces both temporary and permanent alteration of resistance of a nature opposite to that resulting from longitudinal traction.

9. Stress applied equally in all directions diminishes the total and the specific resistance of most metals.

10. The alteration of the melting-point temperature of ice can be readily and accurately determined by observations of the change of resistance produced by fluid pressure on metal wires placed in the ice.

11. Experiments on the permanent alteration of resistance of metal wires produced by stress furnish valuable information respecting the "limit of elasticity" of metals.

12. There are two "critical points" in every metal at which sudden changes occur in the ratio of the permanent extension produced by any load and the load itself, when the latter is gradually and carefully increased. The first of these two points fixes the true "limit of elasticity," and the second the true "breaking-point" of the metal. With iron there are three, and perhaps more "critical points."

13. The "critical points" are evidently in most cases closely related to the moduli of elasticity.

14. The total resistance of most metals is permanently increased by permanent longitudinal extension, but with nickel the total resistance is permanently *decreased*, provided the extension does not pass a certain limit; beyond this limit further extension produces increase of resistance.

15. The rate at which a wire is "running down" under the influence of a load can be very advantageously studied by observing the permanent increase of resistance produced by the load.

16. If P be the "breaking-load" of a metal wire, and p be the load actually on the wire, the decrease per unit of the velocity of the increase of resistance is inversely proportional to $P-p$: so that the actual "breaking-load" of a wire can be calculated from observations of the rate of increase of resistance when a loaded wire is "running down."

17. The above-mentioned proportion holds good not only for one and the same metal but for different metals.

18. The result of experiments on the influence of permanent extension on the temporary alteration of resistance which can be produced by temporary longitudinal stress verifies the statement made in Part I. that "the elasticity of a wire is diminished by permanent extension not exceeding a certain limit, but beyond this limit increased." The effect of permanent extension on the alteration of resistance which can temporarily be produced in nickel by traction is very remarkable.

19. Permanent extension, hammering and torsion produce, even when carried to excess, very small changes in the *specific* electrical resistances of metals. Most metals have their specific resistances increased by strain caused by the above-mentioned processes, provided the strain does not exceed a certain limit: beyond this limit further strain decreases the specific resistance. In the case of iron and nickel, on the contrary, the specific resistance is at first *decreased* and afterwards increased.

20. The strain caused by heating annealed steel to a temperature slightly and very much in excess of that of the room produces effects on the specific resistance of the metal of a kind similar to those caused respectively by small and great mechanical strains.

21. The change of density which can be effected in metals by permanent extension, hammering, or torsion is small.

22. The amount of recovery of electrical conductibility which is produced by time in all metals which are in a state of strain varies considerably with the nature of the metal; with platinum-silver the amount of recovery in a given time is very small, and with German-silver comparatively very large.

23. The recovery of electrical conductivity is in all cases attended with increase of longitudinal and torsional elasticity.

24. Metals may be divided into two classes, as far as the influence of permanent strain on the susceptibility to temporary change of resistance from change of temperature is concerned. In one class the strained wire is most increased in resistance by rise of temperature up to a certain limit, whilst beyond this limit further strain diminishes the first effect. In the other class the converse takes place.

25. There is a close relationship between the thermo-electric properties of strained and unstrained metals and their susceptibility to change of resistance from change of temperature.

26. The elasticity of annealed iron or steel is not *temporarily* but *permanently* increased by raising the temperature of these metals to 100° C. The ductility of annealed iron may also be very considerably and permanently diminished by the same process. Mechanical strain influences the elasticity in the same manner as the strain caused by tempering, and we may say of both kinds of strain that in the case of iron and steel there are three "critical points"—very slight strain increasing, moderate strain diminishing, and excessive strain again increasing both the torsional and the longitudinal elasticity.

27. The temporary alteration of elasticity which is effected in the case of nickel by raising the temperature to 100° C. is very noticeable. Still more remarkable is the temporary alteration of susceptibility to change of resistance from change of stress which is produced by the same means.

28. The electrical resistances of annealed iron, annealed steel, very hard steel, nickel, cobalt, bismuth and zinc are all increased by longitudinal magnetization. The alteration of resistance produced by the magnetization of annealed nickel is very remarkable.

29. The amount of increase of resistance produced in iron and nickel by longitudinal magnetization depends not only upon the magnetism induced, but also upon the magnetizing force, in such a manner that increase of resistance will be produced by increasing the magnetizing force, even when the latter does not cause any appreciable increase of magnetism.

30. The increase of resistance which is produced by magnetization is probably not merely due to the rotation of the molecules of the magnetized substance as molecules, but to the electrical currents, which according to AMPÈRE's hypothesis are constantly circulating round the molecules.

31. The "circular" magnetization which is produced when a current flows through a wire of iron does not appreciably alter the electrical resistance of the wire.

32. The effects of temporary stress and of permanent strain on the alteration by magnetism of the resistance of an iron or nickel wire are of a similar nature to those on the alteration of the magnetic susceptibility of these metals.

33. There is a very striking relationship, both as regards amount and direction, between the alteration of specific resistance, which can be produced in a substance by longitudinal traction and the "rotational coefficient" of the substance.

34. There is evidently an intimate relationship between the "viscosity" of a metal and its specific electrical resistance.