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ABSTRACT

This paper focuses on Michael Faraday's experimental research in electricity in the 1830's. Historical notes related to his work are included as well as experiments, his objectives, and illustrations of equipment for the experiments. Examples from his diary are given so that students can attempt to emulate his honest and systematic manner of recording observations. (SA)

Faraday's Investigation of Electromagnetic Induction

(Experiment #21)

FARADAY'S INVESTIGATION OF ELECTROMAGNETIC INDUCTION

(Part I)

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(Note: Only Faraday's First Series of experiments, Aug. - Nov., 1831, is included in II above, at present. Notes on the Second Series, Dec. 1831 - Jan. 1832, will be distributed later.)

FARADAY'S DISCOVERY OF ELECTROMAGNETIC INDUCTION

Part I

Preface

There is no finer example of the art of experiment than Michael Faraday's famous discovery of the principles of electromagnetic induction in 1831-1832. The combination of simple but inspired probing and testing, of perceptive and honest observation and measurement, and of disciplined imagination is nowhere excelled. Nowhere can one witness the hands, the eyes and the mind working in more complete harmony, with such intense and sustained concentration, and with such spectacular success It is not only the quality of his work and the importance of his achievements that make Faraday's experiments so fascinating and instructive: the account he wrote of them is of a matching quality. In his published papers, written without delay after each phase of the work is completed, Faraday describes in simple, cogent language how he proceeds, step by step to unravel one problem after another, to track down each mystery as it arises, until he attains his goal. As Clerk Maxwell writes of Faraday's "Experimental Researches in Electricity"(1): The student

> "...will there find a strictly contemporary historical account of some of the greatest electrical discoveries and investigations, carried on in an order and succession which could hardly have been improved if the results had been known from the first, and expressed in the language of a man who devoted much of his attention to the methods of accurately describing scientific operations and their results."(2)

Moreover:

> "Faraday shows us his unsuccessful as well as successful experiments, and his crude ideas as well as his developed one, and the reader, however inferior to him in inductive power, feels sympathy even more than admiration, and is tempted to believe that, if he had the opportunity, he too would be a discoverer."(3)

What finer commendation could there be, and from what better source?

The experiments which are of immediate concern here occupied Faraday for some two months, September to October 1831. They represent one of his supreme exertions, and, perhaps, his greatest achievements. Had Faraday rested at this point we could hardly be surprised. But after a break of a few weeks - during which time he writes the published account of his work, he continues, with the same intensity, to explore the ramifications of his new discovery and to extend, revise and clarify the formulation of its basic principle. Faraday's success in one aspect of electricity seems to give him even greater confidence to deal with others. Soon his researches range over the whole domain of electricity - discoveries flow from his work as if from an inexhaustible source. But he is never content; never satisfied that he has reached final certainty or even the final clarification of his own ideas. Twenty years after his first great triumph he returns to this very same subject of electromagnetic induction - now as much to exploit as to establish its principles. Faraday's discovery of 1831 had as profound and lasting an influence on him, as it did on science.

To relive some of Faraday's successes we have available to us now, not only the beautifully written published accounts, but also the reproduction of Faraday's own laboratory diary(4) in which he records his day-to-day observations, commentary and plans. So thoroughly and with such meticulous care and honesty is this kept, that with a little polishing up, they could almost be read as published papers. A comparison of the personal "Diaries" with the published "Experimental Researches" demonstrates - if any such demonstration were necessary - how faithfully Faraday reports in his published accounts what he actually did and observed. Some details are at times omitted, but nothing that <u>might</u> be significant is ever suppressed - whether it be favorable to his conclusions or not.

I. Historical Notes

Faraday's discovery of electromagnetic induction was made some eleven years after Oersted's announcement of the magnetic action of the voltaic current. It was his second notable contribution to electrical science, and one of such magnitude as to establish a leadership which he was to retain for several decades. His first contribution - the spectacular demonstration of continuous circular motion of a magnet under the influence of a current (and vice-versa) - was made in 1821-1822, in the wake of the great excitement stirred by Oersted's discovery; and directly stimulated by the unsuccessful attempts of his seniors at the Royal Institution, Humphry Davy and William Wollaston, to demonstrate a similar sort of motion. Although Faraday at that time (he was 30 years of age) was no stranger to electricity, what he knew of the subject was mainly from what he had read and what he picked up in his day-to-day contacts with Davy and others at the Royal Institution. He must also have acquired an extensive and thorough, if not intimate, knowledge of the subject in the course of preparing, at the instigation of his friend R. Phillips, his "History of the Progress of Electromagnetism" for the Annals of Philosophy. There could hardly have been a more opportune moment for him to become himself part of this history.

There is no difficulty in recognizing in these first forays into electricity the indelible stamp of Faraday's power and style; the forthright, persistent, patient experimental probing; the repeated trial and test with innumerable variations of every idea; the search for the essence of the new phenomenon which will enable him to grasp it as a whole - without reliance on the intermediacy of formal, mathematical deduction - instinctively rather than by logical rational deduction. Yet - the achievement notwithstanding - it is clearly the work of a newcomer to the field rather than of experienced master. The recent discoveries had given the subject of electricity itself a sudden and profound new turn which made all the learned masters of the subject in a sense newcomers - although few recognized this. Faraday was largely unencumbered by the scholarly orthodoxies, and entered into the new electrical science with ingenuous ardour of the novitiate. His experiences and accomplishments as an experimental philosopher were already impressive, but these were in the wholly different field of chemistry In his position at the Royal Institution he is still a "junior"; in the world of science he is as yet a rising star; and in electricity he is making his debut. Here new puzzles and mysteries abound. Intuitively he puts his fingers and directs his attention on the most significant; he poses question after question - and to one major one he finds the answer. He has opened up - to himself - a whole new world of remarkable and perplexing phenomena; but when he left it - for the time being - its mysteries were still mostly unresolved He had produced a remarkable solution to one problem - whose significance was by no means ephemeral - its influence on the development of Ampère's work testifies to that. But the real significance of Faraday's first electrical work was its deep influence on Faraday himself, far more than its immediate impact on the science itself.

For ten years after his demonstration of electromagnetic rotations Faraday made no publicly visible contributions to electrical science. His time and energies were elsewhere directed; but there is little doubt that the problems of electromagnetism, in which he had been so deeply involved for a year or two (1821-22), constantly stirred his mind. The views he had formed he could defend against those of others - for example in his correspondence with Ampère - but they were neither totally satisfactory to himself, nor final. We see from entries in his Diary, how from time-to-time he returns to some unsettled point for a brief check, by experiment of course; and how new notions, though still latent, are beginning to germinate. His knowledge of this field is now sufficiently intimate, and his involvement sufficiently deep for him to follow closely the rapid flow of new discoveries and developments in the experimental art: Practical "galvanometers" based on the "multiplier" principle and made more sensitive by the use of "astatic" needles (Schweigger, Ampère, Nobili); powerful electromagnets (Moll, Sturgeon, Henry); the new thermo-electricity (Seebeck, Nobili, Melloni); and, probably of closest interest, the continued development of Ampère's electrodynamic theory, and the discovery by Arago and investigation by others of the remarkable "magnetism of rotation".

Ampère's demonstrations, ideas, and theories, which issued forth in an incessant stream, dominated the development of electromagnetism in this period; and it was from his "initial" debate in 1822, in challenging Ampère's ideas that Faraday had been led to clarify and strengthen his own views. It is extraordinary to observe in this earnest, well-mannered clash of views, how two individuals, engaged at the very same time in exploring the identical phenomena could adopt such divergent viewpoints For Ampère the aim is always to penetrate, by assertive assumptions if necessary, to the basic logical elements - logical, that is, from the standpoint of one fullyversed in, and deeply committed to the Newtonian method and the mathematical apparatus that it entailed. The abstract, ideal elements - his "current-elements", and the basic, Newtonian type, law-of-force between them - were for Ampère the ultimate realities. What was observed - experimentally - was but an imperfect expression of these; useful of course as a check - with the proper mathematical machinery - of the principles themselves. For Faraday it was precisely the reverse. The experimental observations represented primary facts and they displayed the basic truths. Lacking any facility in formal mathematics, and only a qualitative feeling for dynamical laws, yet gifted with an extraordinarily powerful visual-geometrical sense, he had to, and so often could, visualize or feel the phenomena, intimately and as a whole. Until he had sensed, examined, and tested by actual observation, and, with all the attendant practical circumstances, Faraday could form no theory; without a theory there was, for Ampère, no experiment.

How clearly Ampère expresses his logic in this comment (which he attaches to the French translation of Faraday's first paper on electromagnetic rotation).

> "The attraction and repulsions of the two conducting wires of finite length, discovered by M. Ampère, are likewise not simple facts; it seems to us that one can only give this attribution to those laws of mutual action that one must assume to exist between two points in order that there should result between two infinite assemblages of such points, the phenomena that these actually present to us. This being so, the simple facts cannot be observed directly; but only inferred from the observations with the help of mathematics..."(5)

> Les attractions et les répulsions de deux fils conducteurs d'une longueur finie, découvertes par M. Ampère, ne sont pas non plus des faits simples; il nous semble qu'on ne peut donner ce nom qu'aux lois de l'action mutuelle, qu'il faut admettre entre deux points pour qu'il en résulte, entre deux assemblages d'une infinité de ces points, les phénomènes qu'ils nous présentent; dès lors, les faits simples ne peuvent être observés immédiatement, mais seulement conclus des observations à l'aide du calcul : c'est sous ce point de vue qu'on doit considérer les lois de l'action de deux petites portions de courants électriques, telles que les a données M. Ampère : elles sont confirmées, jusqu'à présent, par tous les phénomènes connus et, en particulier, par ceux que vient de découvrir M. Faraday. (5)

What a contrast is Faraday's confession (to Ampère) of his intuitive probing:

> "I am unfortunate in a want of mathematical knowledge, and the power of entering with facility in abstract reasoning. I am obliged to feel my way by facts closely placed together so

> that it often happens I am left behind in the progress of a branch of science not merely from the want of attention but from the incapability I lay under of following it...On reading your papers and letters, I have no difficulty in following the reasoning, but still at last I seem to want something more on which to steady the conclusion. I fancy the habit I got into of attending too closely to experiment ...chains me down, and I cannot help now and then comparing myself to a timid navigator who, though he might boldly and safely steer across the bay or an ocean by the aid of a compass... is afraid to leave sight of the shore because he understands not the power of the instrument that is to guide him."(6)

When Faraday studied the interactions of a magnet with the voltaic current, he soon saw, and then could not stop seeing, its essential character as one of rotation - of the magnet (pole) and the wire around each other. So ineluctable a feature of the phenomenon must reflect - indeed express - the basic underlying force; a force so wholly different from the orthodox Newtonion attractions and repulsions. And Faraday's belief in the reality of this new force seems placed beyond doubt when he could demonstrate truly <u>continuous</u> rotations. This was not something Ampère's theory had predicted - on the contrary it seemed at first as if the theory denied this possibility. But after the event, it was not difficult for Ampère to show that his theory could - or even should - have predicted such motion; and even to mount his own version of Faraday's demonstrations. Which was more to be trusted: A theory which could explain the phenomenon; or concepts which gave birth to their realization? The issue was not resolved. Faraday stayed with his conviction that the simplicity of Ampère's direct force of action and reaction was illusory. its real significance more "complex"; Ampère with his own conviction that Faraday's apparent rotation force was, far from a contradiction, a result to be obtained from his own fundamental theory, by mathematical deduction. Neither Ampère nor Faraday had any doubts. And yet in the attempt of each to convince the other, each clearly reveals some uneasiness, some suspicion that there may be <u>some</u> measure of truth in the opposite view, and some uncertainty about the completeness of his own. Ampère went on to improve and arrange in its most cogent logical order the experimental basis of his theory and to perfect its mathematical structure. Faraday continued to ponder over the "real" nature of the electric-magnetic relationship.

Disagreement over the nature of the electromagnetic force was not the only issue between Ampère and Faraday. Ampère's theory was set within the framework of a much more sweeping generalization: namely that all magnetism - whether of a common bar-magnet, of the voltaic current, or of the great Earth-magnet itself, was of essence a manifestation of electric currents. Basic interaction must be, according to Ampere, between like elements. (An essentially "modern" view!) If all magnets could be reduced to currents, then <u>all</u> interactions magnet-magnet; magnet current; and the current-current interaction - which Ampère himself had demonstrated and exhaustively analyzed - could be reduced to one and the same On the other hand it was <u>not</u> possible (as the futile attempts of Biot and others showed) to reduce all to magnet-magnet (or in the language of the day - to magnetic fluid) interactions.* This was Ampère's strongest argument - the one that gave him greatest confidence in the essential validity of his viewpoint; but it was one whose force Faraday could hardly have appreciated (at least at the time). What Faraday could see - clearly! - were the ambiguities about the precise form and origin of the Ampèrian currents, and even of Ampère's notions regarding the voltaic current itself. And what he saw was not convincing. How could he erect a whole theoretical superstructure on the foundations - the concept of electric current - which were physically so obscure. If the voltaic current, or current-element, is really the basic element, surely

> "We may, therefore, be allowed to expect that a very clear description will first be offered of it. This however is not the case, and is, I think very much to be regretted, since it renders the rest of the theory considerably obscure."(7)

In fact, Ampère's obscure and vacillating views on the physical nature of the current were hardly relevant to his "theory". That he was, and remained, unsure whether to regard the magnetism produced in iron (etc.) by the electric current as evidence for creation of molecular (Voltaic!) currents or the alignment of pre-existing currents (he implied both possibilities on different occasions); that he (usually!) portrayed the Voltaic current as comprised of <u>two</u> oppositely moving fluids; that he occasionally invoked another (disturbed by the combination or mutual annihilation of the two fluids); that he drew analogies from Fresnel's optical theory of ether vibrations...All this was in reality supererogatory. Although he talked and wrote in 19th century language, he was essentially modern (or 18th century) in his approach. He knew little more about the physical (or chemical)nature of electricity (molecular, Voltaic or otherwise)

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*See note, p. 27.

than his contemporaries (and probably less than some), he could and did address himself to the formal principles, the dynamical symmetries of the electrodynamic interaction. In rejecting electromagnetism as an unsound hybrid his instincts were sound; in asserting that his formal demonstrations demonstrated the validity of his physical principles, they failed him. And it was just these failures, rather than the impressive successes, that Faraday could understand; and there, not suprisingly, display his skepticism.

For Ampère, after 1822-1823, the theory of electrodynamics was a task to be completed: The foundations were laid, the plan was drawn up; now the edifice had to be completed in due proportions and with its final elegance. Faraday in examining the materials rather than the plans, was not even sure it was the proper structure at all. There were too many doubts and difficulties, too many basic problems yet to probe. Electromagnetism was beginning rather than nearing completion.

Now and again an issue arose where the Amperian theory was ambiguous - or even indifferent - as indeed by its very nature it had to be. How were the Amperian currents, induced in iron, for example, related to other physical-chemical properties? Could they be induced in other metals? All metals? And why only metals? The answer from experiment was uncertain.(8) For the theory, and for Ampère, all that really mattered was that whatever it was an electric current or a magnet did, both could do. There was no contradiction with formal theory. But since the formal theory was beyond Faraday's grasp - this carried little conviction to him. Experiment must speak where theory is silent. On occasion experiment did speak - and its voice commanded attention, but its meaning was not grasped. Arago's sensational discovery of the magnetism of rotation was real enough, and surely revealed something important about electromagnetism. Faraday was fully aware of the new discovery and its importance; but his own understanding of the physical nature of electricity and magnetism was no more sufficient to unravel this mystery than was Ampère's. But he did see it as a mystery For Faraday, looking for a deeper physical picture of electricity, and one that might be probed by experiment, the Arago effect could not be shrugged off - it remained, for many years an unsolved, though not an insoluble mystery. Without doubt it came before his mind time and again as a challenge. In his Diary there is only occasional reference to the subject, enough to show that he was fully aware of what lay unresolved. But when in 1831 he makes his impressive assault on the whole issue of electromagnetic induction, the eagerness with which he mentions "Arago's extraordinary experiments" at the earliest opportunity, and, the undesguised sense of triumph with which he announces that he can now "open out a full explanation" of Arago's magnetic phenomena, leaves little doubt about what had for years, been fermenting in his mind. And now also, when he has his own experimental evidence before his own eyes - "strong proof in addition to those advanced by M. Ampère" - he does not hesitate to acknowledge the truth of at least that part of the Ampèrian theory that asserts that magnetism and electric current are manifestations of the same principle.(9) No longer need he struggle with the arcane mathematics which had troubled and eluded him for so long . Now Faraday could take up the exploration of electromagnetism where Ampère had left off.

For Ampère himself mathematical insight together with limited experimental evidence (his formal experiments were consistent with his theory!) had been sufficient from the outset. A more detailed physical picture of the relationship between electricity and magnetism was never his real concern. Indeed, just when it might seem the new phenomenon of magnetism of rotation might provide a real opportunity to test his hypothesis, Ampère seemed little interested. His theory of electrodynamics was now (1824-1825) more or less complete; he was in no need of further experimental evidence to complete the mathematical structure; and as for physical details, it was never deeply concerned with these anyway. For Faraday, the Arago experiments were compelling evidence - but of what? In retrospect it is not hard to see how unlikely it was in a single leap of the imagination to grasp both the new principle involved and the subtle complexities of the situation in which it revealed itself.

From time-to-time Faraday made sporadic efforts to penetrate the mystery, suspicious, as he must have been, that something unrecognized laid beyond. But the efforts were not sustained, and he was no more successful than his contemporaries. He devoted his time and energies to other fields of investigation, his self-confidence and experience as an experimental philosopher grew to full stature. But his concern for the electrical problems that had been raised - partly through his own efforts - was never relinquished. It was unfinished business, brooding in his mind. When, after ten years absence, he turns again his full attention to electromagnetism, it is as if all his pent-up ideas and energies, all the accumulated experience, self-assurance of a master of the experimental art suddenly burst forth to overwhelm the obstacles that have stood in his way so long. The contrast between the inquiring newcomer of 1821 and the master - in his own style - of 1831 could hardly be more striking.

For ten years electromagnetic induction was sought; when it was looked for it was not seen, when it was seen it was not recognized![8] The object was correctly identified, even if not properly defined. The stage was clearly set. We know now that the goal was no mirage. The well-established "theoretical" concepts of the time were too rigidly cast in a mold that failed to recognize the dramatic novelty of the new electromagnetism But experimental techniques were more than adequate. The climax could not long be delayed. When it came in 1831, there could hardly have been anyone now more fitted to play the leading role than Michael Faraday.

Michael Faraday (1791-1867)

It is impossible in a few pages to attempt any proper biographical account of one who has been acclaimed as "the greatest experimental philosopher of all time". E. Whittaker concludes the chapter on "Faraday" in his History of Electricity[10] with this tribute:

> "Amongst experimental philosophers Faraday holds by universal consent the foremost place. The memoirs[11] in which his discoveries are enshrined will never cease to be read with admiration and delight; and future generations will preserve with an affection not less enduring the personal records and familiar letters which recall the memory of his humble and unselfish spirit."

Before turning to the memoirs to see just how Faraday performed what was perhaps his greatest work - the discovery of electromagnetic induction - some few facts of his life and the quality of his own personal records should be recalled.

Michael Faraday, the third child of a journey-man blacksmith James Faraday, and of Margaret Hartwell, of north-of-England stock, was born, (1791), grew up, lived and worked all his life in London His "formal" education, was, in his own words,

> "...of the most ordinary description, consisting of little more than the rudiments of reading, writing and arithmetic. My hours out of school were passed at home or in the street."(12)

It terminated when Faraday was 12 years of age.

In 1804 he became errand boy to a neighboring bookseller - one Mr. George Ribeau, and in the following year, 1805, with him, entered into a seven-year apprenticeship as bookbinder and stationer. He exploited all the opportunities his trade offered him. Of his period in his life, Faraday himself says:

> Whilst an apprentice I loved to read the scientific books which were under my hands, and, amongst them, delighted in Marcet's "Conversations in Chemistry," and the electrical treatises in the "Encyclopædia Britannica." I made such simple experiments in chemistry as could be defrayed in their expense by a few pence per week, and also constructed an electrical machine, first with a glass phial, and afterwards with a real cylinder, as well as other electrical apparatus of a corresponding kind.' He told a friend that Watts 'On the Mind' first made him think, and that his attention was turned to science by the article 'Electricity' in an encyclopædia he was employed to bind.
>
> 'My master,' he says, 'allowed me to go occasionally of an evening to hear the lectures delivered by Mr. Tatum on natural philosophy at his house, 53 Dorset Street, Fleet Street. I obtained a knowledge of these lectures by bills in the streets and shop-windows near his house. The hour was eight o'clock in the evening. The charge was one shilling per lecture, and my brother Robert (who was three years older and followed his father's business) made me a present of the money for several. I attended twelve or thirteen lectures between February 19, 1810, and September 26, 1811. It was at these lectures I first became acquainted with Magrath, Newton, Nicol, and others.' (13)

His biographer, Bence-Jones, writes:

> In his earliest note-book he wrote down the names of the books and subjects that interested him: this he called '"The Philosophical Miscellany," being a collection of notices, occurrences, events, &c., relating to the arts and sciences, collected from the public papers, reviews, magazines, and other miscellaneous works; intended,' he says, 'to promote both amusement and instruction, and also to corroborate or invalidate those theories which are continually starting into the world of science. Collected by M. Faraday, 1809-10.' (14)

Among the books and subjects which are mentioned in this volume are, 'Description of a Pyropneumatic Apparatus,' and 'Experiments on the Ocular Spectra of Light and Colours,' by Dr. Darwin, from *Ackerman's Repository*; 'Lightning,' and 'Electric Fish and Electricity,' from *Gentleman's Magazine*; 'Meteorolites,' from the *Evangelical Magazine*; 'Water Spouts,' from the *Zoological Magazine*; 'Formation of Snow,' from *Sturm's Reflections*; 'To loosen Glass Stopples,' from the *Lady's Magazine*; 'To convert two Liquids into a Solid,' 'Oxygen Gas,' 'Hydrogen Gas,' 'Nitric and Carbonic Acid Gas,' 'Oxymuriate of Potash,' from *Conversations in Chemistry*.

'Galvanism:' 'Mr. Davy has announced to the Royal Society a great discovery in chemistry—the fixed alkalies have been decomposed by the galvanic battery,' from *Chemical Observer*; 'Galvanism and a Description of a Galvanometer,' from the *Literary Panorama*. (14)

In Mrs. Marcet's "Conversations in Chemistry", and through the little experiments by which he could realize what he read was true to fact, he found for himself "an anchor in chemical knowledge and clung fast to it". In Mr. Tatum's lectures his interest was stirred in the whole world of science. Mr. Ribeau was a kind master, and Faraday was not unhappy in his work, but as the period of apprenticeship drew to a close, his conviction grew that a life in trade was not what he desired. To his friends he talked of "giving up trade and taking to science". In 1812, when he was 21, a fortuitous circumstance (but had it not been this - it would surely have been some other) settled his resolve. As Faraday himself recalls:

'During my apprenticeship I had the good fortune, through the kindness of Mr. Dance, who was a customer of my master's shop and also a member of the Royal Institution, to hear four of the last lectures of Sir H. Davy in that locality.[1] The dates of these lectures were February 29, March 14, April 8 and 10, 1812. Of these I made notes, and then wrote out the lectures in a fuller form, interspersing them with such drawings as I could make. The desire to be engaged in scientific occupation, even though of the lowest kind, induced me, whilst an apprentice, to write, in my ignorance of the world and simplicity of my mind, to Sir Joseph Banks, then President of the Royal Society. Naturally enough, "no answer" was the reply left with the porter.'

During this period Faraday formed a friendship - through the weekly Tatum lectures and the City Philosophical Society held at Tatum's house - with a Benjamin Abbot, whose formal education had been a more extensive than Faraday's. His correspondence with Abbot provides some fascinating glimpses of Faraday's interest at this time. In his first letter to Abbot he writes:

> 'I have lately made a few simple galvanic experiments, merely to illustrate to myself the first principles of the science. I was going to Knight's to obtain some nickel, and bethought me that they had malleable zinc. I inquired and bought some—have you seen any yet? The first portion I obtained was in the thinnest pieces possible—observe, in a flattened state. It was, they informed me, thin enough for the electric stick, or, as I before called it, De Luc's electric column. I obtained it for the purpose of forming discs, with which and copper to make a little battery. The first I completed contained the immense number of seven pairs of plates!!! and of the immense size of halfpence each!!!!!! (15)

And in later letters, the same year (1812):

> 'Definitions, dear A., are valuable things; I like them very much, and will be glad, when you meet with clever ones, if you will transcribe them. I am exceedingly well pleased with Dr. Thomson's definition of Chemistry; he calls it the science of insensible motions: "Chemistry is that science which treats of those events or changes in natural bodies which consist of insensible motions," in contradistinction to mechanics, which treats of sensible motions.
>
> 'How do you define idleness?
>
> 'I forgot to insert a query when at the proper place, though I think an investigation of it would be of importance to the science of chemistry, and perhaps electricity. Several of the metals, when rubbed, emit a peculiar smell, and more particularly tin. Now, smells are generally supposed to be caused by particles of the body that are given off. If so, then it introduces to our notice a very volatile property of those metals. But I suspect their electric states are concerned; and then we have an operation of that fluid that has seldom been noticed, and yet requires accounting for before the science can be completed.

'I have again gone over your letter, but am so blinded that I cannot see any subject except chlorine to write on; but before entering on what I intend shall fill up the letter, I will ask your pardon for having maintained an opinion against one who was so ready to give his own up. I suspect from that circumstance I am wrong . . . . With respect to chlorine, if we intend to debate the question of its simple or compound nature, we have begun at a wrong point, or rather at no point at all. Conscious of this, I will at this time answer your present objections but briefly, and then give the best statement I can of the subject. The muriate of soda is a compound of chlorine and sodium, and as chlorine in the theory is esteemed a simple substance, I conceive that the name of chlor*ate* of sodium is improper; *ate* and *ite* are the terminations of the generic name of salts, and convey to our minds an idea of the acid that the base is combined with. But chlorine is not an acid;' (16)

The lack of success of his ingenuous application to Sir Joseph Banks, at the Royal Society, did not lessen Faraday's passionate interest in science, and his resolve to leave his trade - he was now a journeyman bookbinder - was given added force by the uncongenial temperament of his new employer - one Mr. de la Roche. Faraday no longer awaited an opportunity; he created one. In his own words (of 1829):

'My desire to escape from trade, which I thought vicious and selfish, and to enter into the service of Science, which I imagined made its pursuers amiable and liberal, induced me at last to take the bold and simple step of writing to Sir H. Davy, expressing my wishes, and a hope that if an opportunity came in his way he would favour my views; at the same time, I sent the notes I had taken of his lectures.

'Finally, through his good efforts, I went to the Royal Institution, early in March of 1813, as assistant in the laboratory; and in October of the same year went with him abroad, as his assistant in experiments and in writing. I returned with him in April 1815, resumed my station in the Royal Institution, and have, as you know, ever since remained there.

At the age of 22 Faraday is embarked on a lifetime of scientific labours that will be unparalled in intensity and fecundity. He had hardly begun his services as assistant when fortune provided him the opportunity to accompany Davy on a grand tour of Europe (France, Switzerland, Italy). The journal he kept and the letters he wrote home show his lively and sensitive response to the multitude of new experiences. He meets Ampère, Clement and Désormes, and Gay-Lussac in Paris (they discuss chemical matters - especially the new chemistry of Iodine), De la Rive in Geneva, and Volta ("a hale elderly man bearing the red ribbon; and very free in conversation") in Milan. In Genoa he assisted Davy in experiments on the Electric Torpedo; in Florence at the Accademia del Cimento he saw "Galileo's first telescope" - that with which he discovered Jupiter's satellites; he ascended Mount Vesuvius and explored its crater by both day and night. And he saw his first glowworm!

Back in London in 1815; in 1816 he lectured regularly at the City Philosophical Society on such diverse ("chemical") topics as the attraction of cohesion, chemical affinity, radiant matter, and on oxygen, chlorine, iodine, fluorine, hydrogen and nitrogen. The same year he published his first paper - "An analysis of native caustic lime". His second apprenticeship - this one as a chemist - was now complete.

In 1820 he is collaborating with Stodart on the alloys of steel (the Indian steel "wootz" in particular); and publishes his first paper in the Transactions of the Royal Society - on two new compounds of chlorine and carbon.

In 1821, the year in which he demonstrates continuous electromagnetic rotations, he publishes in addition to papers on this subject, others on alloys, on the changing of vegetable colors as an alkaline property, on the actions of salts on tumeric paper, and one on a new compound of iodine and carbon. In 1823 he liquified chlorine and published numerous papers on subjects as diverse as the condensation of gases, gunpowder, and the purple tint of glass affected by light. His accomplishments and stature as an investigator are beyond question; he is elected a corresponding member of the French Academy of Sciences, and a Fellow of the Royal Society, London. The following year he investigates new compounds of hydrogen and carbon produced by distillation of oil and discovers what he calls bicarburate of hydrogen (now known as benzine).

In 1821 Faraday married Sarah Barnard (the third daughter of an Elder of the Sandemanian Church), with whom he lived at the Royal Institution for 46 years.

From 1825 onwards, as a consequence of his own activities, and Davy's deteriorating health, he begins to assume a leading role in the Royal Institution; at first as Director of the Laboratory, later as Lecturer, and finally (in 1833) as the Fullerian Professor of Chemistry. His whole energy is now devoted to experimental philosophy, to the search for the latent relationships between the infinite variety of natural phenomena, to find and formulate Nature's Laws. He will continue as Davy did before him

> "...To interrogate Nature with power, not simply as a scholar passive and seeking to understand her operations, but rather as a master, active with his own instruments."

In 1829, Davy died and Faraday succeeded him. In 1831 Faraday was at an age when many would consider their major work to be completed. But as we know, Faraday was then just at the beginning of a great scientific career. John Tyndall, who joined Faraday at the Royal Institution in 1851, and later succeeded him, gives this picture of Faraday at the time.(17)

> "In 1831 we have him at the climax of his intellectual strength, forty years of age, stored with knowledge, and full of original power. Through reading, lecturing, and experimenting, he had become thoroughly familiar with electrical science: he saw where light was needed and expansion possible. The phenomenon of ordinary electric induction belonged, as it were, to the alphabet of his knowledge: he knew that under ordinary circumstances the presence of an electrified body was sufficient to excite, by induction, an unelectrified body. He knew that the wire which carried an electric current was an electrified body, and still that all attempts had failed to make it excite in other wires a state similar to its own.
>
> What was the reason of this failure? Faraday could never work from the experiments of others, however clearly described. He knew well that from every experiment issued a kind of radiation, luminous in different degrees to different minds, and he hardly trusted himself to reason upon an experiment that he had not seen. In the autum of 1831 he began to repeat the experiments with electric currents, which, up to that time, had produced no positive result."

II. Faraday's Experiments (1831-1832)

As outstanding as were Faraday's discoveries, his style is no less so. Repetition of his experiments provides a unique opportunity not only to learn something about the fundamentals of electromagnetism, but also to witness at close hand the work of a supreme exponent of the experimental art.

Faraday's notebooks and reports are exemplary. To capture the spirit of his work, the student should attempt to emulate (but not simply to copy) his impeccably honest and systematic manner of recording observations, comments and conjectures.

Observations should be recorded faithfully at each step in the actual sequence the experiments are made (and in a laboratory notebook - not in loose scraps). Comments, conjectures, notes for future tests, etc. should be interpolated, as they occur.

On the completion of any series of experiments, an attempt should be made to summarize what has been observed, what has been conjectured, and what conclusions may be drawn now, after the experiments. At this stage also, notes may be made of further tests which could be made to test these conclusions.

Throughout, the student should make every effort to distinguish, scrupulously, between

a) Observations recorded at the time made and in proper sequence.

b) Queries, conjectures, ideas, etc. arising in the course of the experiment, and recorded briefly at the time.

c) Conclusions drawn after the experiments.

Faraday's reports are so lucidly written and beautifully organized that it would be foolish and impertinent to attempt to improve on them. They are here followed step-by-step with only minor comments.

The equipment Faraday used reflected both the current state of technique and the fortuitous circumstances that determined what was, at a particular moment, at hand. The former should be respected - if one is to appreciate the problems encountered and the skill with which these are resolved. But where technique particulars are only incidental, things are adapted to practical convenience.* There

*See pp. 30-37 for technical details.

are two issues of a general nature: i) the sources of current, and ii) the galvanometer used.

i) For current sources Faraday used various arrangements of the voltaic battery, with effective voltages ranging from 1 or 2 to 50 or 100. Currents probably rarely exceeded about 1 amp. Such simple voltaic cells (Cu,Zn) are not difficult to reproduce; but if the materials (especially the zinc) are not to be constantly replaced, their use must be carefully managed (Probably impractical with classes of elementary students). A low-voltage storage battery (2 to 6 volts), with a fixed resistor in series to limit the current to one ampere is a reasonable compromise with historical fidelity (but meters should not be put in circuit; a length of resistance wire which glows perceptibly would be a reasonable indicator of steady current). (See p. 37)

ii) In many experiments the sensitivity, time-constant, internal resistance, etc. of the galvanometer do play a key role. Simple moving-iron fixed-coil galvanometers of the type Faraday used are easily reproduced; and there are many lessons to be learned in doing so. (See p. 36)

The order of the experiments below is that followed in Faraday's published papers (reproduced in Experimental Researches in Electricity, Vol. I, pp. 1-75) - identified by paragraph (§) numbers. This order is not the precise order in which Faraday actually made the experiments. As Faraday declares:

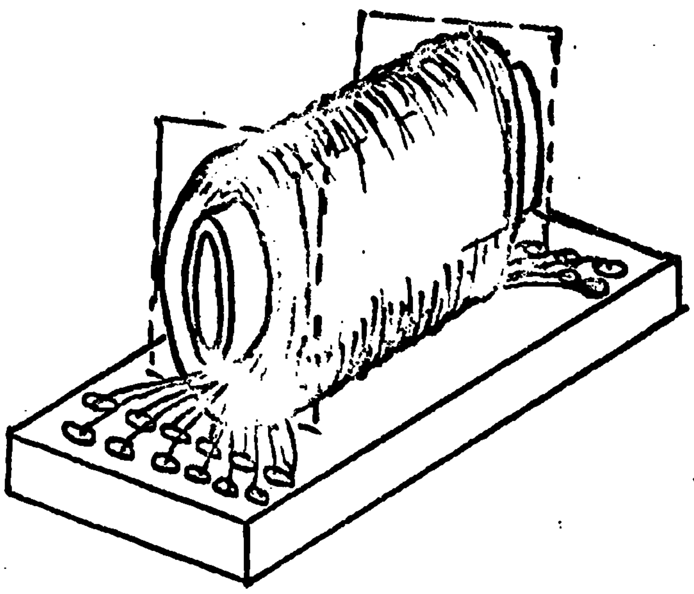
> "These results I propose describing, not as they were obtained, but in such a manner as to give the most concise view of the whole."

This is not then his laboratory record; but such a record does exist: the Diary, and there one can see with equal clarity, and in more intimate detail, the way Faraday's hands and eyes and mind works. The accompanying dates (below) refer to those in the Diary for the corresponding experiments.

§ 6-25 Currents Induced by Currents

- § 6-12. (Diary Sept. 12, 1831): Notice how the closest proximity of the several coils is attained, in accord with the prevalent ideas of most favorable conditions for "induced" effects.

Two compound "coils" are made, and these serve for a variety of experiments:

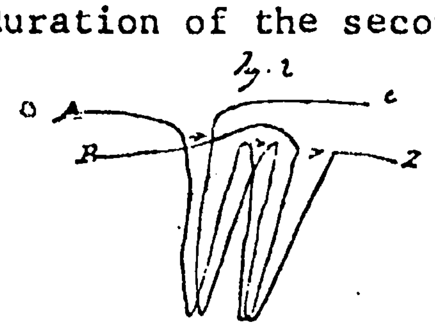


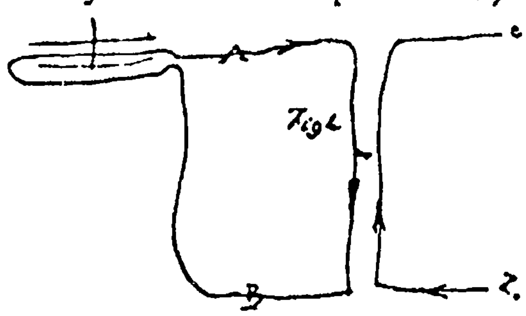
i) ~300 ft of copper cotton-covered wire (approximately 1mm diameter, or 20 gauge) wound as 12 separate layers, each of approximately 30 turns; all same helicity. Insulating cloth between layers. Bind with cotton and varnish, etc. Ends of each of the 12 coils brought out separately so that various connections can be made. Wound on hollow (hardboard, hardwood) former; 3" diameter.

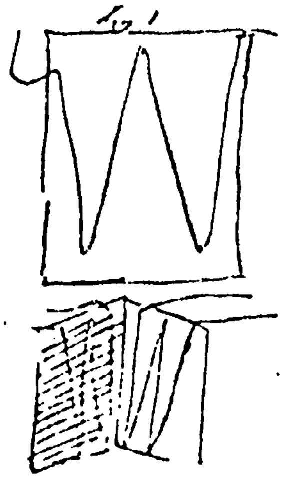
ii) As i) but with alternate layers of copper and soft-iron wire.

<u>§ 13-17. (Diary Oct. 18th)</u>: Faraday is now fully convinced that the induced effects are transient and rapid. (He had been exploring induction now for 7 or 8 weeks). The idea that a rapid discharge of electricity, though not able to overcome the inertia of the galvanometer needle, may be able to influence magnetic properties (on account of the presumed small inertia of the "magnetic fluid), was earlier used by H. Davy and others (1820) to demonstrate that the current in a Leyden-jar discharge (ordinary electricity) had magnetic properties similar to the galvanic current (as in Oersted's experiment). The combined effects of a "make" and "break" of the primary do not cancel - according to Faraday (§ 16). Check this experimentally. Could it be related to the non-constant source of current? Or to the magnetic properties of the "steel needle"?

That "magnetisation" is a more sensitive test than a sensitive (?) galvanometer may seem surprising. (Some rough calculations might be made to check, from this result, the typical duration of the secondary current "pulse".)

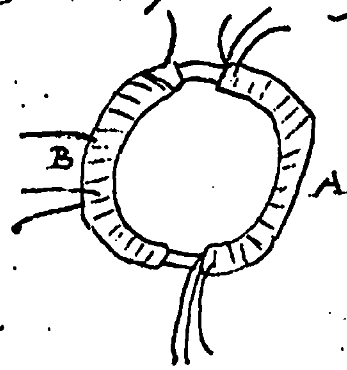






Diary: Dec. 26th (c.f. § 18, 19)

insulated from the other. Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length the direction being as with the former coils this side call B.



Charged a battery of 10 pr. plates 4 inches square. Made the coil on B side one coil and connected its extremities by a copper wire passing to a distance and just over a magnetic needle (3 feet from iron ring). Then connected the ends of one of the pieces on A side with battery. immediately a sensible effect on needle. It oscillated & settled at last in original position. On breaking connection of A side with Battery again a disturbance of the needle.

The entry recording the first successful experiment in electromagnetic induction. August 29, 1831 (*slightly reduced*)

(See § 27-34)

§18,19. (Diary Dec. 26th): In the previous experiments there has been change in the current, but no physical movement of the current-carrying wires. Is actual change of current necessary? In this test Faraday moves the wires, without changing the current. Make sure the two circuits do not make contact (use insulating paper). The direction of the secondary currents (with respect to the primary) is most significant. Record carefully and unambiguously. (c.f. p.   for details of apparatus)

§20,21. (Diary Oct. 1st): That "induced" effects are neither inhibited nor enhanced by a prior standing current may seem obvious now, but certainly not to Faraday (Even if the e.m.f.'s superposed "linearly", there was little familiarity with - and certainly no tacit assumption of - the notion of a strictly "ohmic" resistance. Ohm's own work (1825/27) certainly gave no such assurance - and in any event was essentially unknown to Faraday . Faraday's experimental check is typical of his thoroughness.

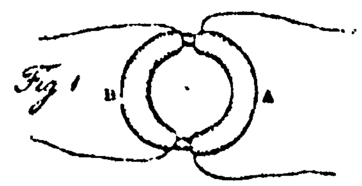
§22-25: Faraday's attempt at an "intuitive" interpretation of the differences, as observed, between the Leyden-jar discharge, and induced transient currents, is extremely interesting; but it hardly comprises a proper - or even semi-quantitative - analysis of this more complex situation.

§26: Since all the experiments, so far!, refer to effects produced by changing electric currents, Faraday chooses a term - Voltaic-electric induction - which presumes no more than has been observed! This concern with terminology, and the fear that by injudicious choice unwarranted assumptions can be engendered, or encouraged, recurs time and again in Faraday's writings.

§27-59 Electricity from Magnetism

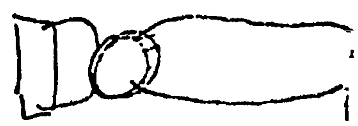
§27-34. Current produced magnetism. (Diary Aug. 29; Sept. 1st - 19th): This is the realization of Faraday's ten year old dream; to "make" electricity from magnetism; his first unambiguous demonstration of electromagnetic-induction and clear recognition of its "time-dependent" properties (See: Diary entry for Aug. 29th, 1831, opposite). The apparatus is also the prototype of all the transformers of the future! He is still producing the "induced" currents by changing other (primary) currents; but the greatly magnified effects with iron (though not with other metals; 34) leaves little doubt about the role of magnetism.

The basic apparatus (§ 27) comprises a triple coil (A) of 3 X 100 turns and a double coil (B) of 2 X 100 turns, all wound (20 gauge copper wire suitable) in the same helical direction; all the ends are brought out separately.



Experimental Researches in Electricity § 27.

The induced effects in this case are so strong that a very simple home-made "galvanometer" (say 20 turns wire and a compass needle) suffices to observe them. This is what Faraday appears to have used in his first experiments. See sketch: (p. 34).



Marginal Sketch: Diary: Aug. 29, 1831

Notice again the care with which the directions of the induced effect is observed and specified. Also (§ 33) the indifference of the induced currents to standing currents (c.f. § 20,21). Similar, but not quite so powerful, effects of iron are observed by introducing iron into the coil (§ 6) used earlier (§ 34).

§ 36-40. "Ordinary" Magnetism. (Diary Sept. 24th): There is now - for Faraday - a final step to take: to produce electricty without any voltaic battery at all; by magnetism alone. And knowing how to look and what to look for, success is assured and speedy (§ 36-38). The Diary entry of Sept. 24th records, "Hence here distinct conversion of Magnetism into Electricity."

The experiments show that induced currents are produced not only by a change in the state of magnetization of the material (§ 36-38), but also that "mere approximation of a magnet, and not its formation in situ", suffices. (Diary Oct. 17th), (§ 39).

Fig. 2.

Experimental Researches § 36.

§41-43. (Diary Oct. 15th, 17th): Notice the developing galvanometric techniques - which are to become progressively more important.

§44-59. Use of More Powerful Magnets*. (Diary Oct. 28th): To explore more fully the character of the new induced electrical currents, Faraday needs more powerful apparatus. There is no time (nor money!) to build this; he uses whatever opportunity is available - now it is the large magnet of the Royal Society. With this he can examine in detail and in many variations: Change in magnetization, change in position, presence or absence of iron, change in the form and the number of turns of wire, etc.

The basic principle emerges: Any change in the magnetic condition near a conductor "induces" (transient) currents in it. (The experiment teaches much more, of course: Under what conditions the effects are small or large.)

Faraday now believes he has experimental evidence to vindicate Ampère: Changing magnetism - natural and artificial - just like changing current can induce electricity. The basic identity of magnetism and electrical current now seems beyond doubt. But he is still cautious, and retains - at least tentatively - a distinction in terminology, between galvano-electric and magneto-electric induction.

Even with this more powerful apparatus Faraday is not able to verify that his induced currents have all the properties of familiar voltaic current: chemical, heating, physiological, etc. But he can excite frog convulsions (still the hallmark of electricity?!).

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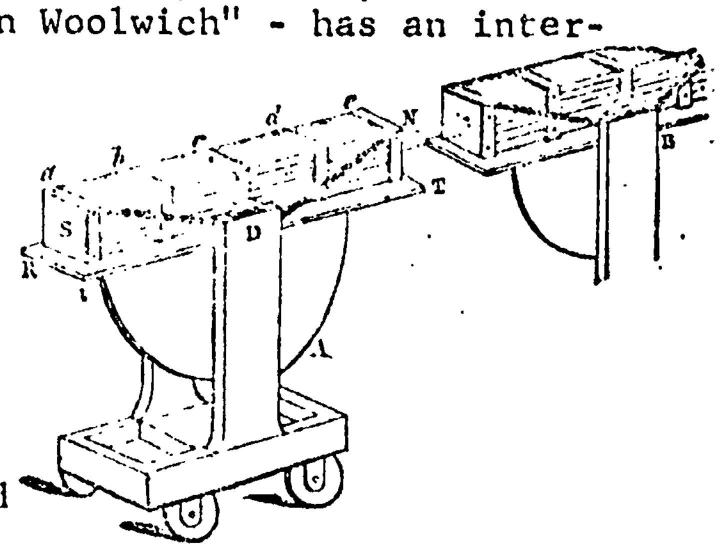
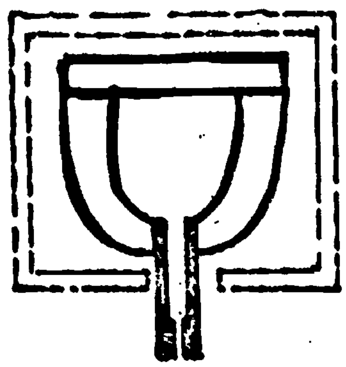
*The large Gowin Knight magnet of the Royal Society - "at present in the charge of Mr. Christie, at his house in Woolwich" - has an interesting history of its own. It was built by Dr. Gowin Knight (1713-1772), a London physician, who was the first to succeed in making large and very powerful steel magnets, by a process which he kept secret. It was only revealed after his death when his great magnet was taken apart, and then reassembled, but never fully restored to its original power! When assembled the two sections each comprised some 240 separate magnets, of total weight 500 lbs, and stood



The large Gowin-Knight magnet Faraday uses is sufficient but neither necessary nor especially designed for his purposes. Similar experiments can be performed with much smaller (modern) permanent magnets, adapted with suitable pole extensions. The main body of the magnet should be enclosed in a non-magnetic (wood) box with the pole-extensions protruding (to reduce the likelihood of damage - to apparatus or fingers!



§ 60-80. The Electro-tonic State

Here Faraday is striving to form some comprehensive physical picture (no mathematics!) of the phenomena. It is not so much a "theory" as one mode of regarding all the various induced effects. Because the predominant feature is their transience, he suggests that they are associated with a change of state of the conductor: For example, turning-on the (primary) current induces, in the "other" (secondary) conductor a new, "electro-tonic", state. When the primary current is turned off, the secondary conductor relapses to its former, normal, state. Induced currents occur only when the state changes. Perhaps one can detect here some implicit analogy to ordinary (electric) induction; but Faraday, appealing as always to experiment (§ 63), finds that, as far as he can detect, there is nothing resembling ordinary electric induction in this case.

Although Faraday very soon abandons this concept of the "electro-tonic" state the discussions in these sections do show his remarkable intuition for what is significant. He seems - as one of his contemporaries (Kohlrausch) put it - "to smell the truth".*

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about four feet high. Gowin Knight was the first to hold an English patent in the class of Electricity and Magnetism (1766). He also used a technique that was the precursor of the modern "sintered" metal magnet.

*See note p. 27.

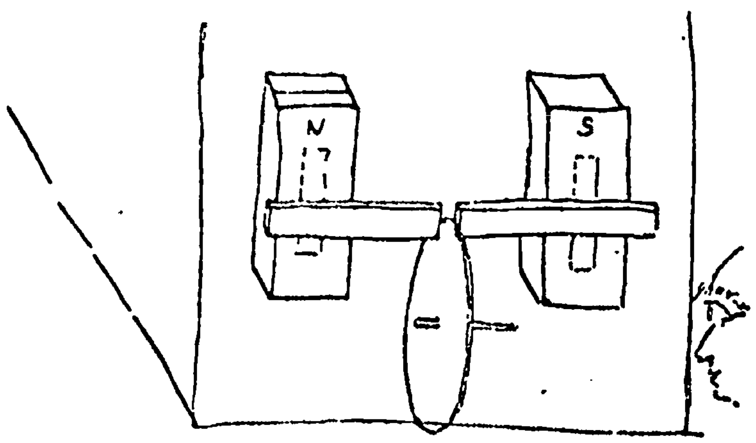
§ 81-139 Moving Conductors, Continuous Currents, Arago Effect

All of the experiments described in this section were the work of two days - Oct. 28th and Nov. 4th, 1831!

§ 84-101. Rotating Disc Experiments (Diary Oct. 28th): A somewhat scaled down apparatus is adequate: Copper disc 8" diameter and 1/8" thick; instead of mercury, colloidal graphite ("aquadag"), is used to make contact; magnet - as above. (p. 23)

Galvanometer (§ 87): As Faraday describes it, "...roughly made, yet sufficiently delicate". It uses the astatic principle, that had already been introduced by others (Nobili, for example). Why Faraday makes the upper needle the stronger is puzzling (A slip? Yet the same statement is made in the Diary!).

An adequate galvanometer can be constructed from ordinary sewing needles, nylon thread and a coil of about 20 turns of 20 gauge wire (See p. 36) for details). (Note: this is one of the earlies examples of a formalized galvanometric "instrument" being used as a modular research tool. In succeding decades it will be developed and elaborated extensively.)

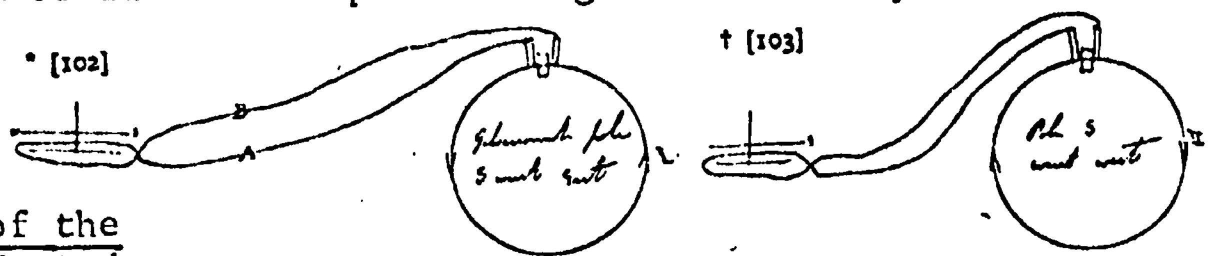


Marginal Sketch from Diary. Oct. 28th, 1831

(Notice the position of the eye; an important part of any experiment!)

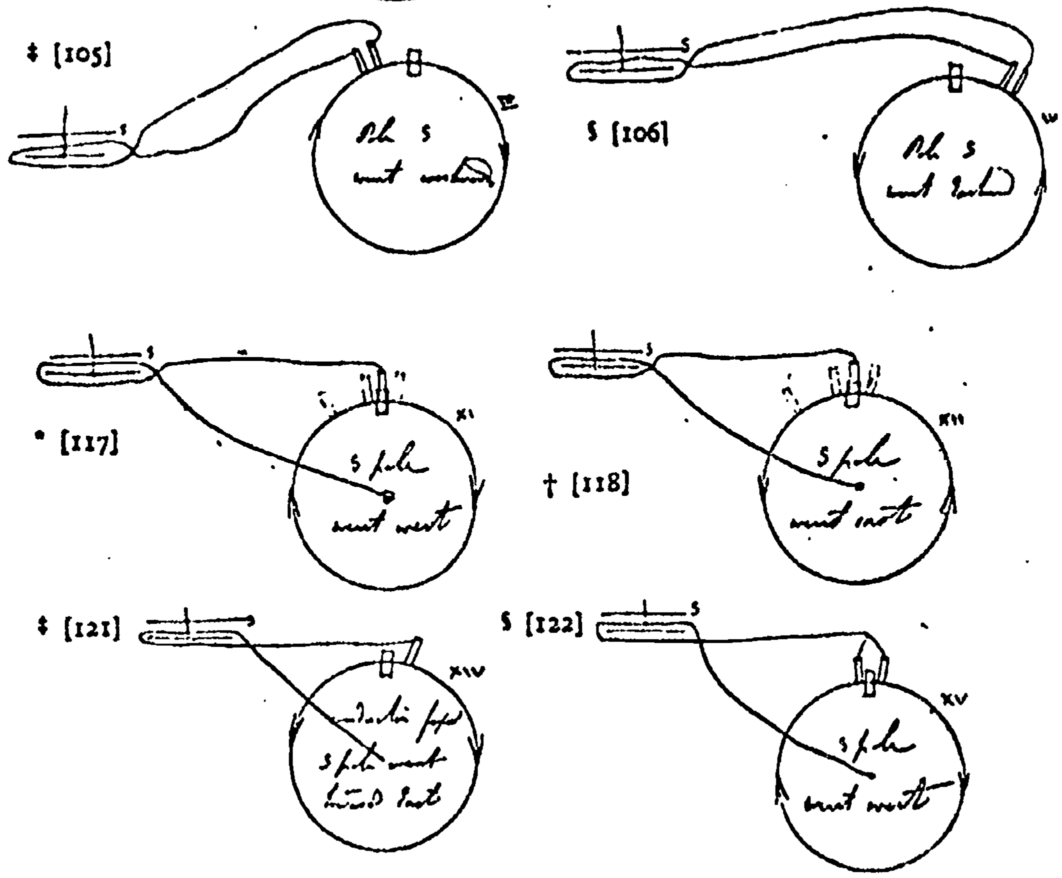
In these experiments, Faraday has two objectives in mind: First, to see whether continuous induced currents are possible; and if so, under what conditions; second, to solve the mystery of the Arago effect. As regards the first, he had earlier (Diary Oct. 24th) already had some success with linearly moving copper strip rather than a rotating disc. The use of rotation in the search for continuity is quite natural; it is also highly reminiscent of Faraday's 1821 success with a continuously rotating electric "motor".

The extraordinary thoroughness with which Faraday examines all the possible variations so as to pin down essential features is nowhere more evident than in these experiments. And his problem is not only to discover the principles involved, but also to express them."The law which governs the evolution of electricity by magnetoelectrical induction, is very simple, although rather difficult to express." For Faraday this has to be done in words - without recourse to formal, logical yet often opaque mathematics. But in reality it is experiments rather than words that reveals the real nature of "magneto-electric" or "galvano-electric" - or to contain both in a single term: electromagnetic induction. And the grand momentum of all this experimenting is not easily arrested!



Some Samples of the Arrangements Tested

(Faraday's Diary Oct. 28th, 1831 and Nov. 4th, 1831)



§ 101-112. Linear Motion (Diary Oct. 24, 28): These further elucidate the essential features of electromagnetic induction. There is no need for the magnet to change, or even for the conductor to move from one place to another of different magnetic (field) strength. (N.B. the concept of magnetic field is nowhere introduced by Faraday, at this stage!)

§ 119-131. Interpretation of Arago Effect: From the new principles governing the manner in which currents are induced, together with his earlier (1821/22)and thereafter) notions about the manner in which currents act mechanically on magnets (his transverse force), Faraday now has a clear picture of the essence of the Aragò effects. He describes these effects with, perhaps, exaggerated simplicity as "precisely the same kind as the electromagnetic rotations which I had the good fortune to discover some years ago"-a statement which was misinterpreted by some as a claim, by Faraday, to have in essence discovered the Arago effect in 1821! (See note p.27)

131-139. Effects in Different Metals: The Arago effect was well known to be quite different - in magnitude - for different metals. It was natural then for Faraday to examine whether the variation derived from a difference in the electromagnetic inducing force (E.M.F.) or some other property of the material. This question is taken up much more fully a little later (§193, 211; Diary Dec. 26, 1831, Jan. 7th, 1832).

The experiments continue; but stop for a brief spell to record and publish what he has already discovered and achieved.

The achievements are already monumental: The principles of electromagnetic induction; the first continuous production of current electromagnetically - the prototype of the dynamo; the principle of the transformer; and a new method for science of exploring the "magnetic field" - by the electromagnetic induction principle - a principle that will soon be exploited by Gauss, Weber and Faraday himself.

As remarkable as the achievements is the style. Step-by-step, Faraday proceeds remorselessly - as if he knows the exact destination. But not a step is missed, and there is hardly a false one: it is as if he is not content to reach his climatic discovery, but to demonstrate that, by following the logic of experiment, arrival at this destination is inevitable. What matter that, as Faraday himself confesses, the experiments were not ordered precisely "as they were obtained, but in such a manner as to give the most concise view of the whole." However obtained, the inexorable power of experiment is inescapable. What a contrast, for example, to the experiments of Ampère which are almost parenthetical footnotes; Q.E.D.'s to a preconceived theory. And what a contrast to the naive Baconian notion of an ordered collection of observations from which generalizations are made inductively. Science is all too commonly divided into its logical (theoretical - mathematical) and empirical (observational - experimental) aspects. Here in Faraday's work is a supreme example of the inseparable combination of experiment and theory, a sequence of observations and deduction which wholly merits Faraday's own designation of his researches as "experimental philosophy."

Additional Notes:

Note re p. 7: Ampère did, of course, himself finally demonstrate the equivalence of the electric current and magnetic interaction; the whole closed circuit could be represented by an equivalent magnetic dipole layer bounded by the current. But from the outset he insists that the fundamental theory must be based on the interaction of (infintisemal) elements, and not surprisingly these are located in the physical elements - currents, magnets, etc. - that are interacting In this sense no distribution of magnetic sources within the current-carrying conductors (and a wire in particular) can reproduce the forces outside. In contrast, is Ampère's faith that the appropriate distribution of currents inside a magnet can account for all the forces between magnets and currents and between magnets themselves - as well as between currents and currents.

Note re p. 27: Since the E.M.F. in a closed circuit in a magnetic field can be expressed in terms of the changes in the "state" of the system; thus:

$$\text{EMF} = \frac{d}{dt}\oint \bar{A} \cdot d\bar{s} ,$$

($\bar{A}$ is the vector-potential at each point of the wire), some parallels have been drawn between the vector-potential and Faraday's electrotonic state. However, in the context in which Faraday introduces this term he surely has in mind some physical state of the wire (or conductor) itself; whereas the expression $\oint \bar{A}\cdot d\bar{s}$ represents rather the state of the whole system. Maxwell writes:

> "The scientific value of Faraday's conception of an electrotonic state consists in its directing the mind to lay hold of a certain quantity, on the changes of which the actual phenomena depend. Without a much greater degree of development than Faraday gave it, this conception does not easily lend itself to the explanation of the phenomena."(18)

Note re p. 26: What seems to Faraday as the essential feature here is the transversality of the force between magnet and current; and also now the transverse nature ($\bar{V} \times \bar{B}$) of the induced currents. (All this is in contrast to the Amperian view of direct action along the line joining the elements). In a sense both the induced current and its interaction with the magnet can be considered as manifestations of the Lorentz force; $e \cdot \bar{V} \cdot \bar{B}$; and in this sense Faraday's "intuitive" perception of the whole phenomenon is remarkably accurate.

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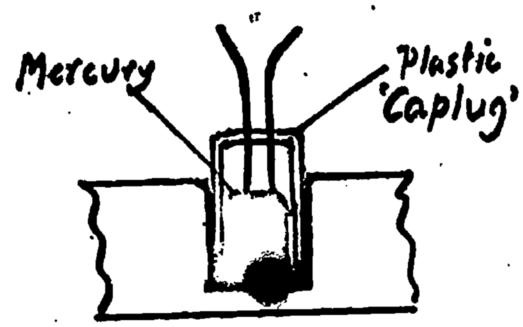
1) M. Faraday, Ref. I, above.
2) J. C. Maxwell. Ref. IV, Vol I, p. ix.
3) Ibid. Vol. II, p. 176 (528).
4) M. Faraday. Ref. II.
5) A. M. Ampere. Ref. III. Vol II. p.185.
6) Letter of Faraday to Ampere. Sept. 1822. (Correspondence du Grand Ampère Paris, 1936-43).
7) M. Faraday. Annals of Philosophy, New Series. Vol 2 1821.
8) See Notes: (Barnard-Columbia History of Physics Laboratory) "The Search for Electromagnetic Induction", 1975.
9) M. Faraday. Ref. I. p. 16.
10) E. Whittaker. Ref. above. Vol I. Chap VI.
11) M. Faraday. Ref. I.
12) Bence Jones. Ref. VI. p. 9.
13) Ibid. p. 11.
14) Ibid. pp. 12, 13.
15) Ibid. p. 17.
16) Ibid. pp. 26, 27.
17) J. Tyndall. Ref. V. pp. 21-22.
18) J. C. Maxwell. Ref. IV. Vol II. p. 188.

IV Apparatus

1. Contacts

Many experiments involve very small potential-differences: Good contacts are necessary. Small mercury cups into which copper wires dipped was a canonical method in Ampère-Faraday's days. It has its drawbacks today! But the method is flexible, and with proper care and arrangement can be used safely. Usually the "cup" is a hole bored in hardwood and sealed. To avoid spilling mercury, the cup is covered with a tightly fitting cap ("caplugs") in the top of which holes are pierced to admit wires. This arrangement is almost spill proof Nevertheless it is prudent to place apparatus with mercury cups on trays! (c.f. p. 32).



Alternatively, wire ends can be well-tinned, and used in conjunction with terminals with well-tinned binding surfaces. Occasional cleaning may be necessary.

2. Batteries, etc.

Currents may be supplied from storage batteries, D.C. power-supplies, or from holes-in-the-wall: None of which were available to Faraday. A simple voltaic cell (E.M.F.$\sim$0.8V) is easily made, and quite adequate for many experiments. E.g.: A copper-zinc pair, surface area$\sim$600sq. cm. in dilute salt solution will give a short circuited current of$\sim$2 amp. The arrangement should permit the plates to be withdrawn from the solution when the cell is not in use.

3. Galvanometers

The moving-needle, suspended on silk thread (nylon) was the standard instrument in the period 1820-1840. It assumed many progressively more sophisticated forms. Faraday used several, some with few turns (voltage-sensitive), others with many turns (current-sensitive). The basis elements are shown (for a simple, non-astatic) in (a), p. 36. A pair of useful, general prupose coils, might be 50 turns each of 18 gauge (approximately 0.04" diameter) insulated copper wire. Total wire length: 20 feet on each coil; resistance$\sim$ 1/10 ohm. It is useful to bring out coil-endings to four separate terminals, so that the coils can be used either in series, in parallel, or in opposition - as a "differential" instrument. Faraday uses this method on occasion. Page 36 ,(b), shows a suitable former for winding the coils; (c) the coils mounted on base, with divided circle above; (d) a simple method for adjusting the height of the needle; (e) and (f) arrangement of astatic pairs - one inside coils and the other above (it can also act as pointer). In (e) the needle is held together with fine twisted copper wire. (g) shows an assembled galvanometer. Some draught-shield is essential. If fabricated from lucite, care must be taken to avoid electrostatic charging. The bracket holding the nylon-thread-cum-needle should be adjustable at its base - for alignment. (h) shows a fancier assembly in which the needle-height can be adjusted from without. (i) and (j) illustrate the coil-former and assembly of a more elaborately built (and higher resistance, many turns) galvanometer

Needles for the galvanometer (sewing or fine knitting) can be magnetized by using a small coil (~1/4" i.d., 4" long, ~1000 turns) through which a large current (storage battery, ~10 amps) may be momentarily passed. A simple arrangement should be set up to check the magnetization of the needles (time oscillations in earth's field).

4. Magnets

Round or flat Alnico magnets (6" long) are more than adequate for experiments §36-40,p.21.

For rotating disc experiments a permanent magnet, such as Edmonds #70476 or # 71501 should be satisfactory, when fitted with suitable extension poles.

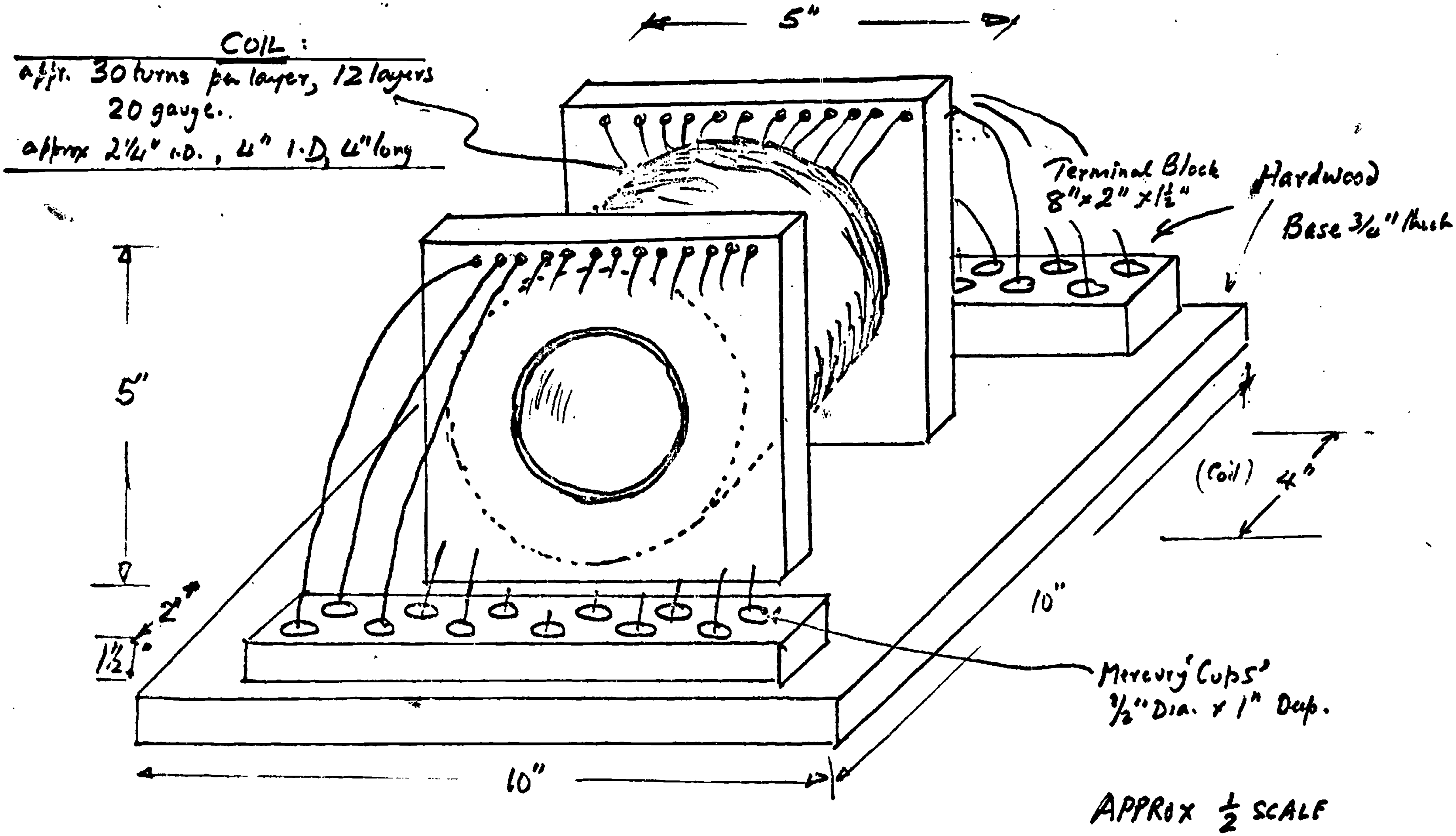
5. Rotating Disc

A copper disc 16" diameter, 1/8" is suitable. It is mounted on a copper or brass axis (1/2" diameter) in simple bearings so as to rotate (in a vertical plane) at a few revolutions per second. The disc, bearings, and pulleys are all mounted on a wooden base which can be raised or lowered. (See photograph).

Contacts are made - either to the rim of the disc or to the 1/2" spindle - by means of graphite-bushes (as used in ordinary electrical motors), spring-mounted in convenient wooden handles. Metal surfaces should be painted with colloidal graphite suspension (Aquadag) for good electrical contact and lubrication.

Note also: Good electrical contact between spindle and disc is essential. Tin and clean matching surfaces before bolting together. (c.f. p.35).

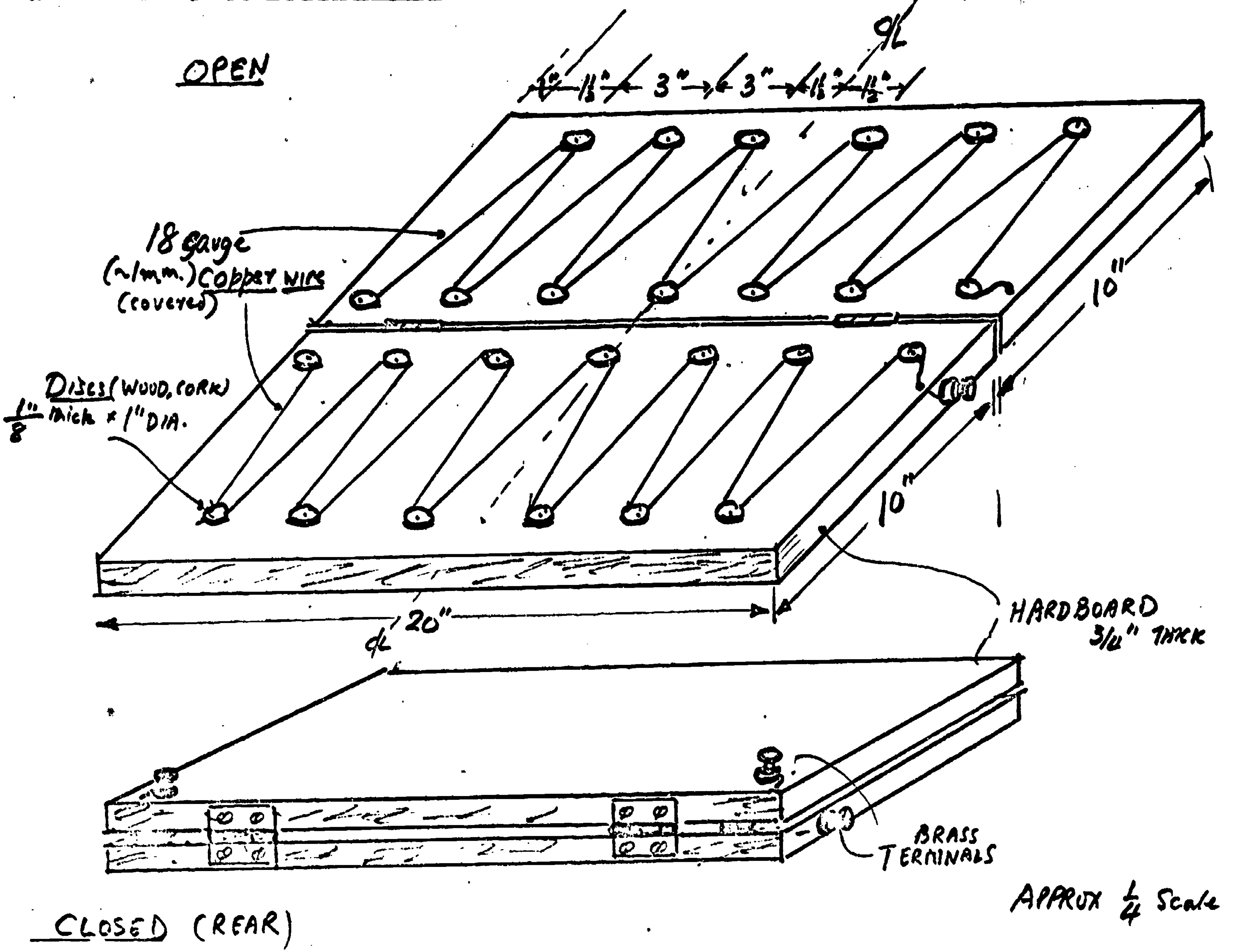
FARADAY · TWELVE LAYER COIL §.6. etc.



FARADAY : TWELVE LAYER COIL § 6 etc.

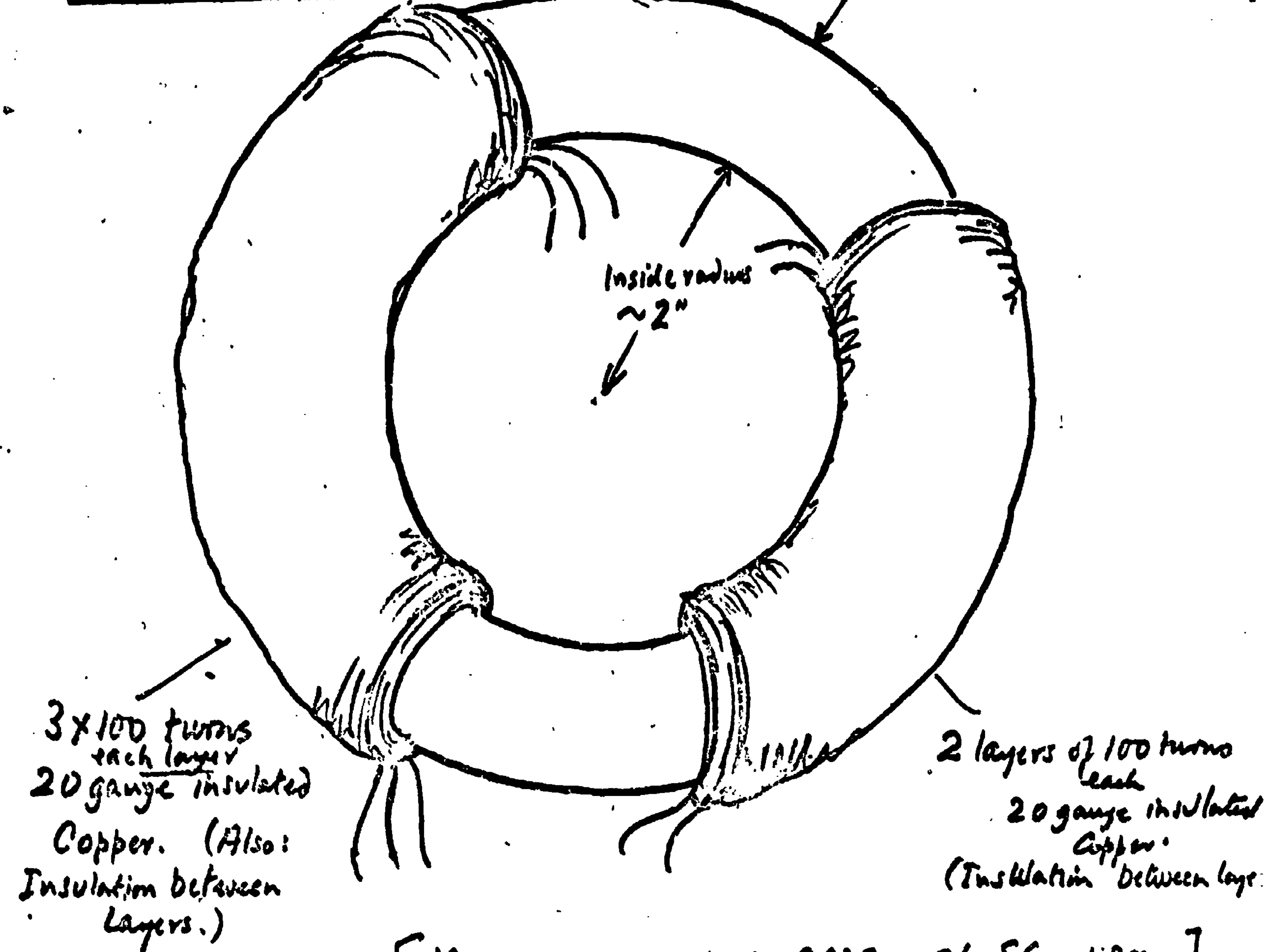
July 3rd/75.

FARADAY



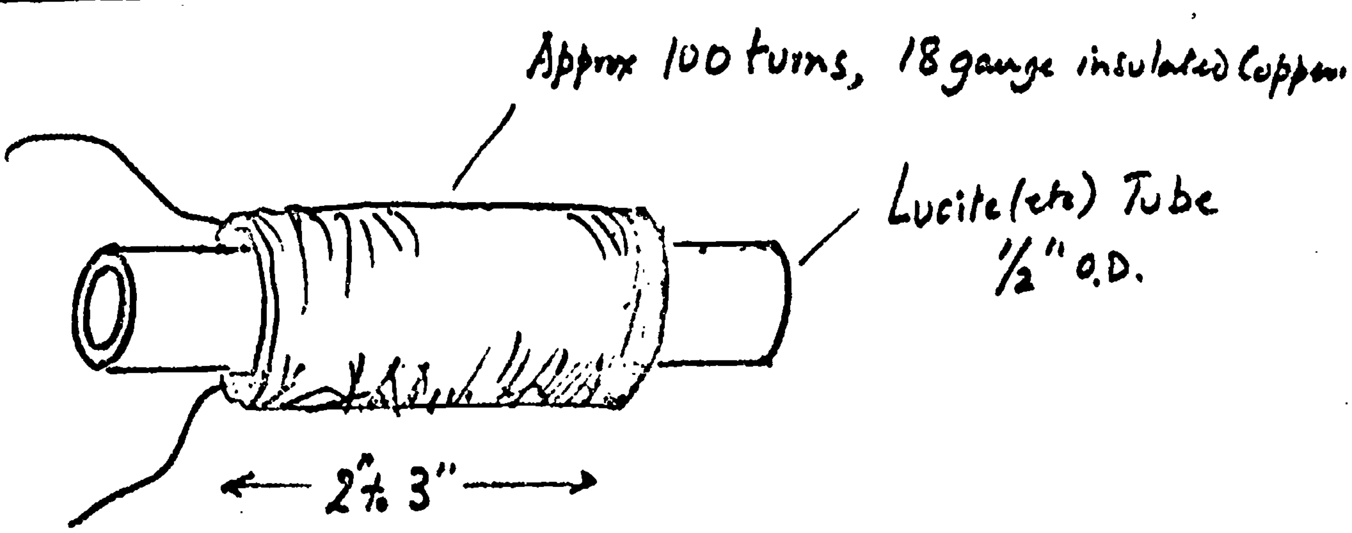
FARADY: DOUBLE CIRCUIT (§18, 19)

"TRANSFORMER" §27-34



[MOUNTED ON WOOD-BASE : Cf. §6. p.28.]

MAGNETISING COIL. §13-17



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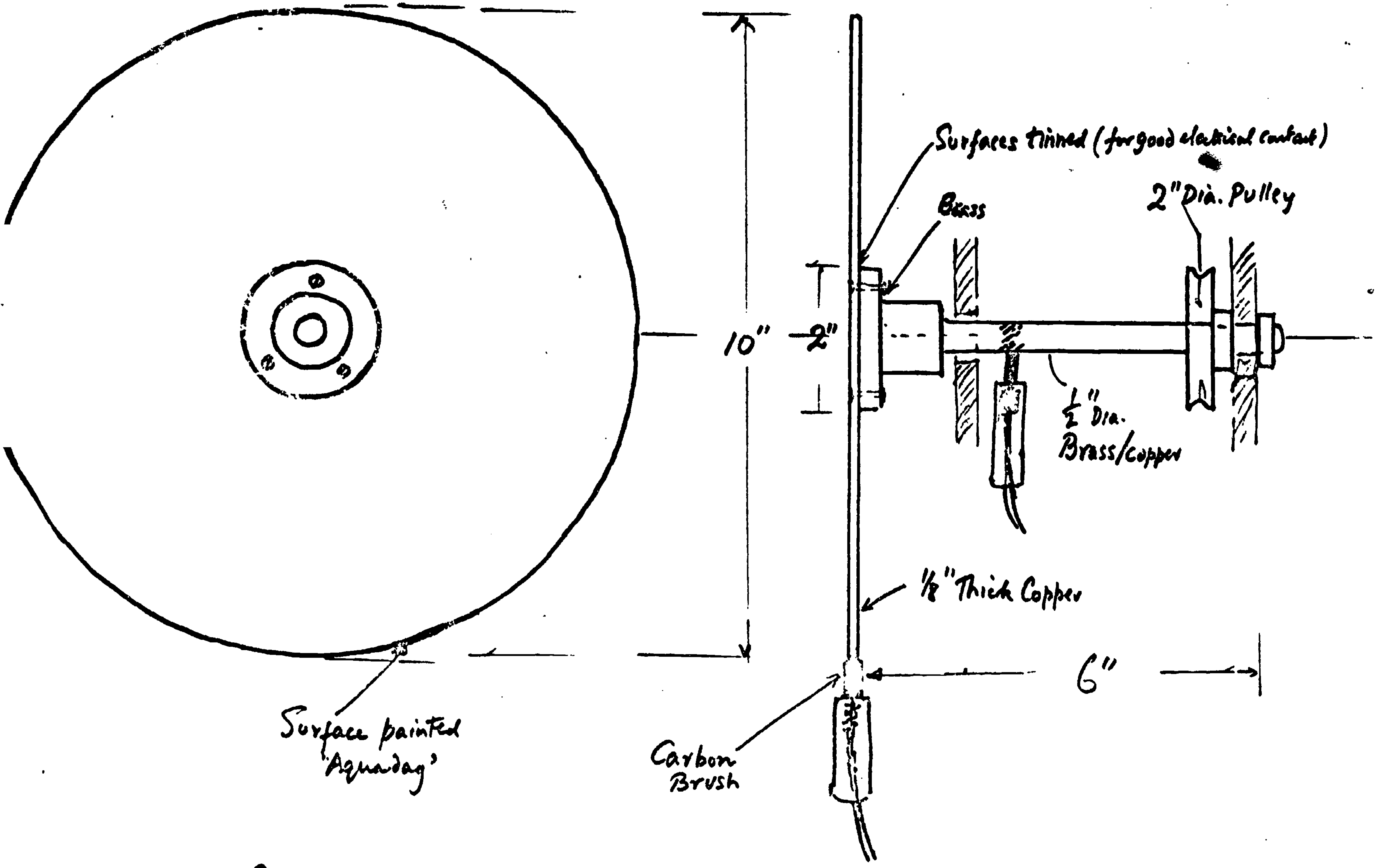
FARADAY: §13-17; §27-34

FARADAY: ROTATING DISC



FARADAY: ROTATING DISC §

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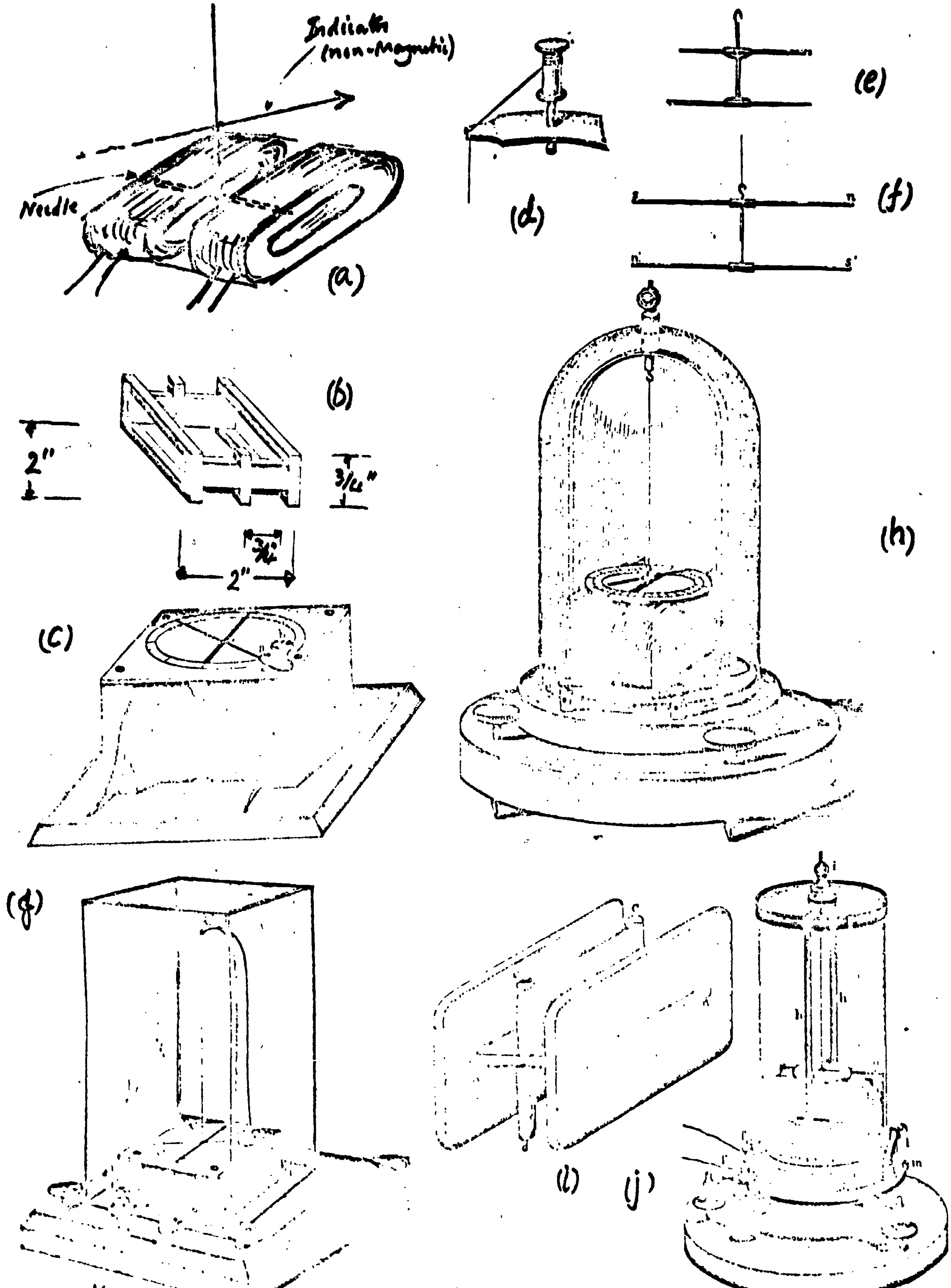
FARADAY: GALVANOMETERS



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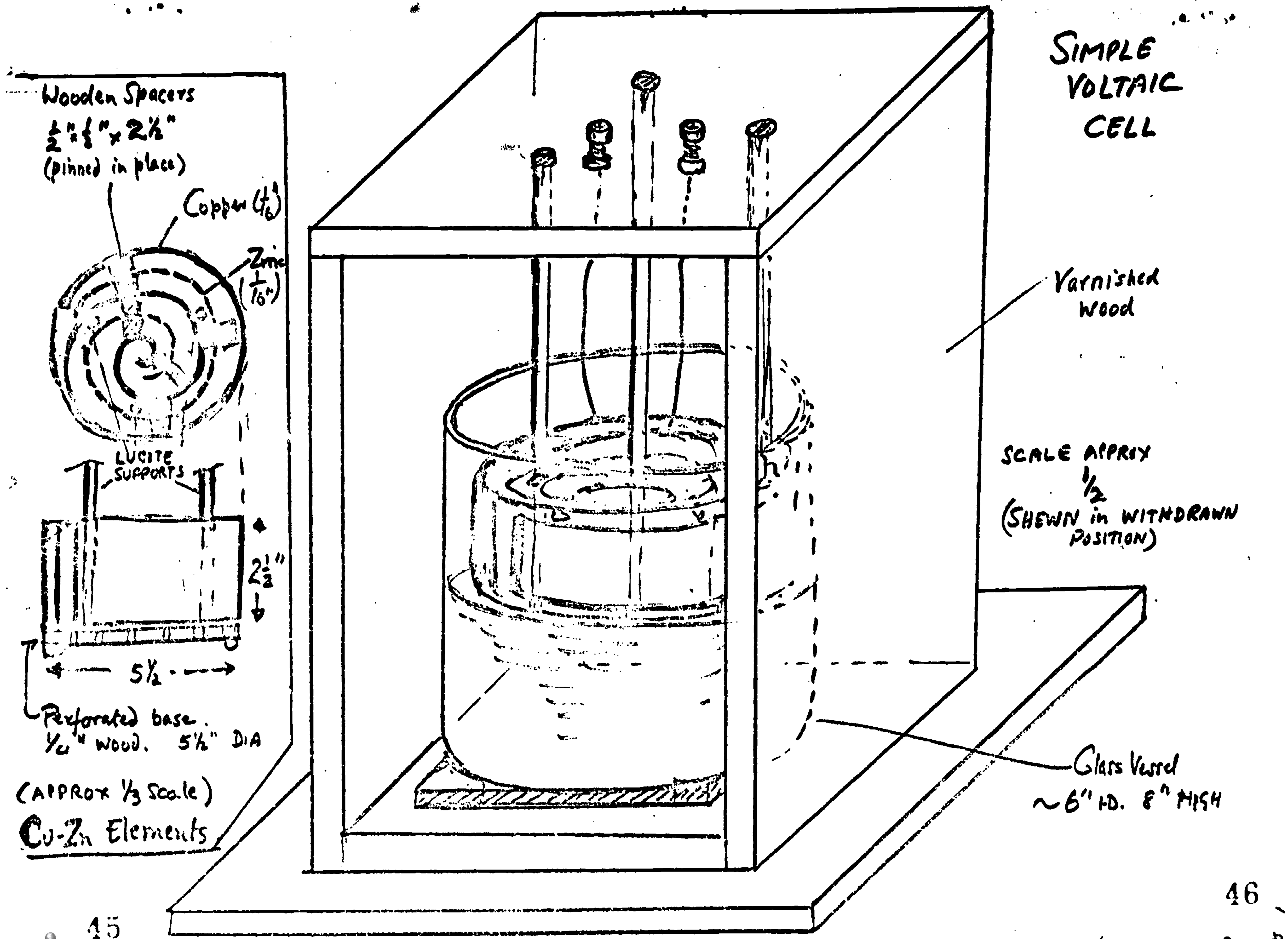
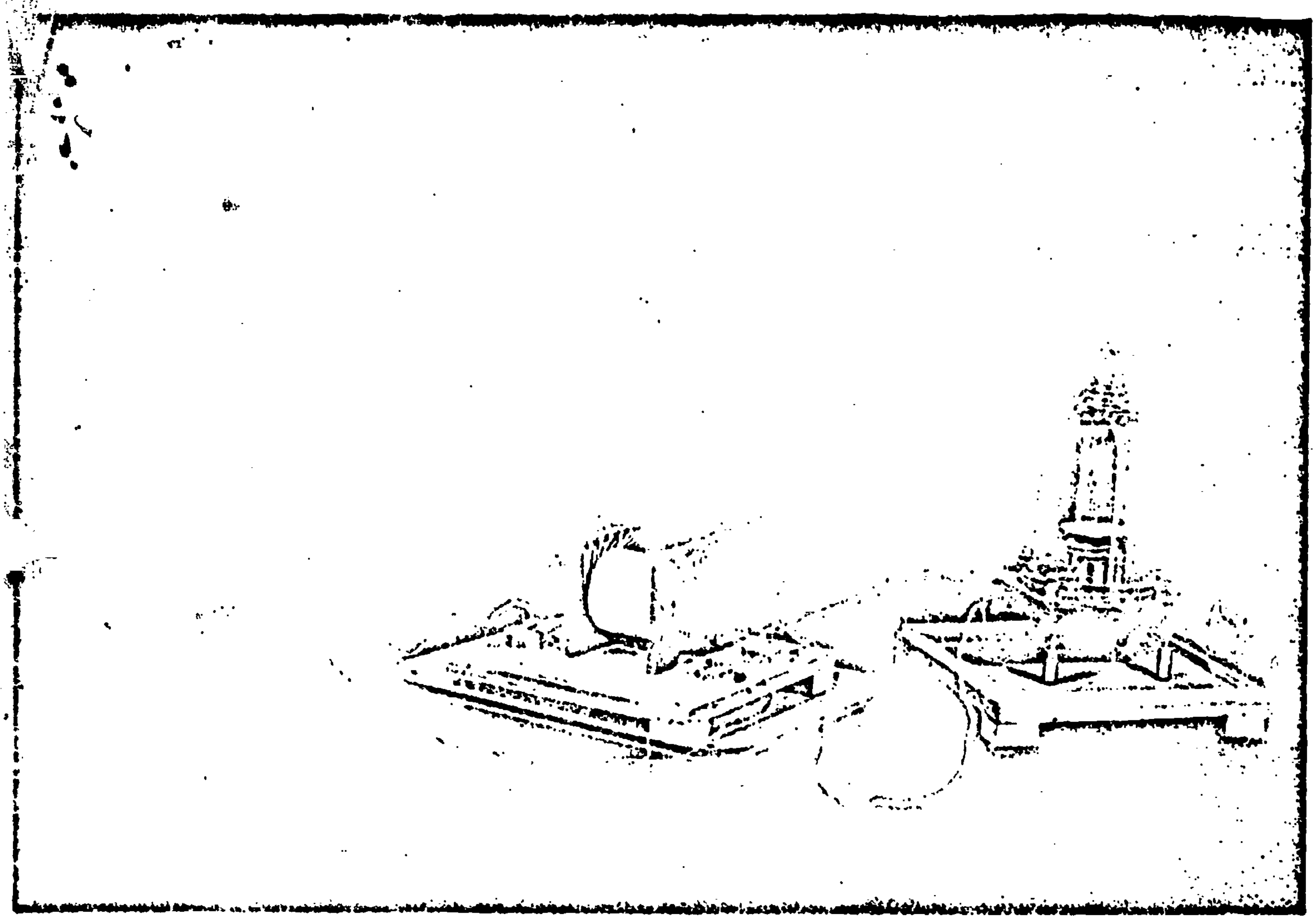
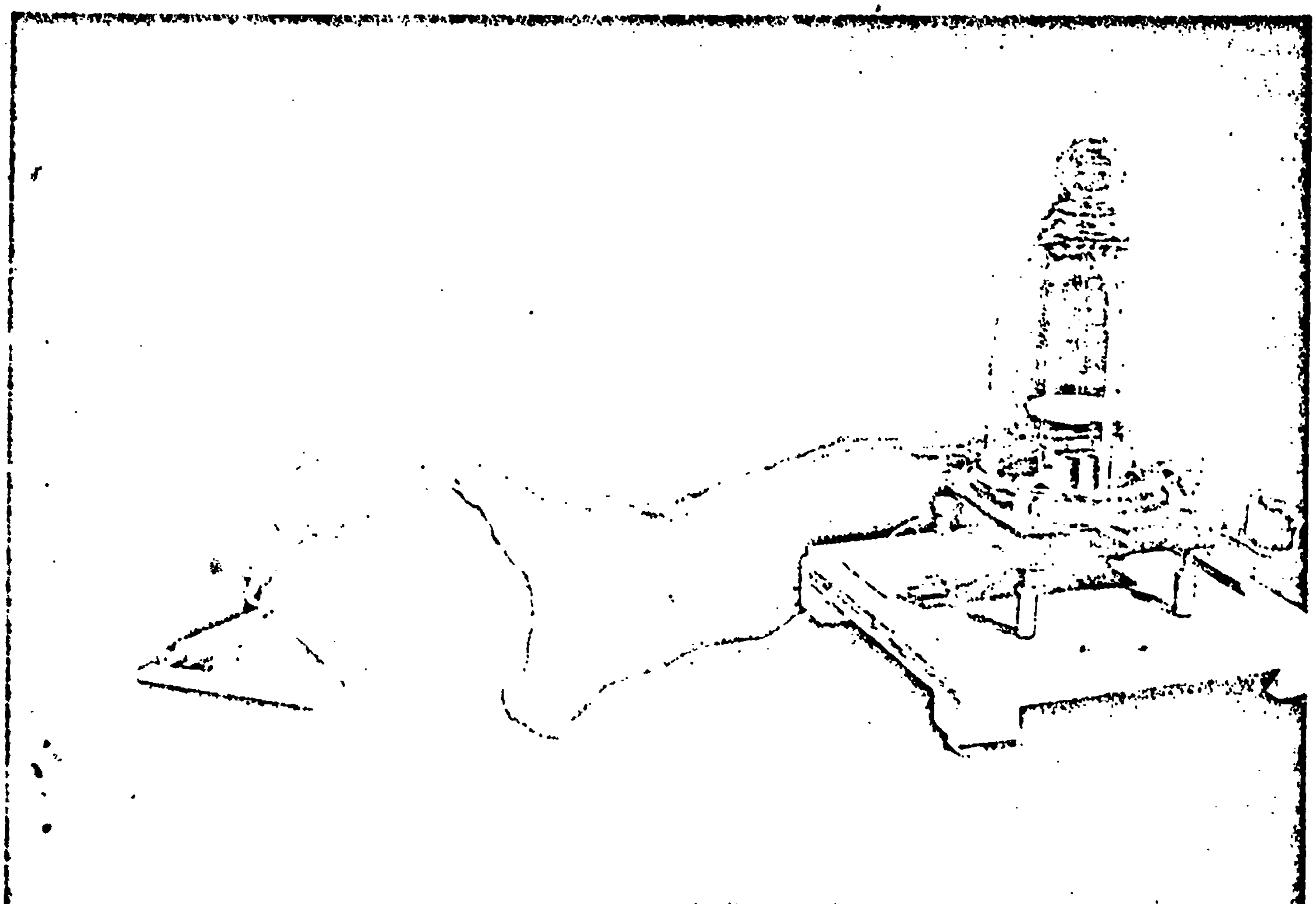

SIMPLE VOLTAIC CELL
Wooden Spacers
1/2" x 1/8" x 2 1/2"
(pinned in place)
Copper
Zinc (1/16")
LUCITE SUPPORTS
2 1/2"
5 1/2
Perforated base. 1/4" wood. 5 1/2" DIA
(APPROX 1/3 Scale)
Cu-Zn Elements
Varnished wood
SCALE APPROX 1/2
(SHEWN in WITHDRAWN POSITION)
Glass Vessel
~6" I.D. 8" HIGH



Voltaic Cell Key Coil (v. pp. 19, 32) Galvanometer



Coil Magnets (v. p. 21) 47