What is the Measure of Electricity?[1]

Howard J. Fisher

What is the measure of electricity? The question itself raises questions. For not all things are susceptible to measure; and even when they appear to be, it is not always clear whether "measure" applies to them as wholes, or only in certain respects. For purposes of this talk, let me propose that a measure of something must, at minimum, enable us to speak of that thing in terms of *more* and *less*. Faraday inherited an electrical vocabulary that appraised electricity as more and less in two respects: first, in *quantity*; and second, in *intensity*. At the outset of Faraday's researches, neither he nor anyone else had been able to state just what these two characteristics were, nor to explain how they related to one another. On the other hand, everybody had *some* rough and practical idea of them, as we may gather from Faraday's unassuming characterization in the Third Series:

> The term quantity in electricity is perhaps sufficiently definite as to sense; the term intensity is more difficult to define strictly. I am using both terms in their ordinary and accepted meaning. [360, note]

If Faraday regarded the term "quantity" as relatively straightforward, it is probably because at the time he began his researches, the conventional idiom of electrical thinking was that of *electric fluid*, a special kind of substance, thought to be endowed with the power to attract or repel other portions of electric fluid. Electric fluid was either *vitreous*, like that which could be evolved upon glass surfaces, or *resinous*, like that which could be produced on rubber, gum, amber, and similar materials. Portions of unlike fluids attracted one another; portions of like fluids repelled each other; and the more fluid there was, the stronger that attraction or repulsion would be. It is easy to know what we mean by "quantity" if electricity is a fluid. But *is* it a fluid? And how can we know?

In contrast, as Faraday implies, the fluid language fails to offer a similarly clear image of *intensity*. What can it mean for a *fluid* to be more or less "intense"? Faraday will seek, and perhaps he will find, a clearer understanding of both these terms.

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As the Third Series opens, we find Faraday in almost the same position as Socrates of the *Meno*; for how can we hope to know the properties of electricity unless we first know *what* electricity actually *is*? We well remember Meno's reply when Socrates asked after the "what" of virtue:

> *Meno*. "There will be no difficulty, Socrates, in answering that. Take first the virtue of a man: it is to know how to administer the state, in which effort he will benefit his friends and injure his enemies, and will take care not to suffer injury himself. A woman's virtue may also be easily described: it is to order her house, and keep what is indoors,

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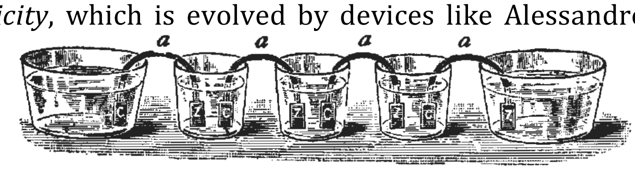
> and obey her husband. Every age, every condition of life, young or old, male, or female, bond or free, has a different virtue....” [71]

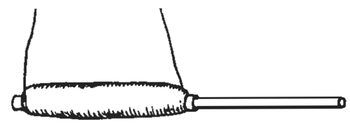
Meno is positively exultant as he contemplates the rich variety of virtues! How disheartening is it, then, to consider that the electrical science of Faraday’s time, though professing to seek a unitary account of electricity, can offer little more than a Meno-like catalog of “electricities.” These include:

- *Voltaic electricity*, which is evolved by devices like Alessandro Volta’s “cups.”

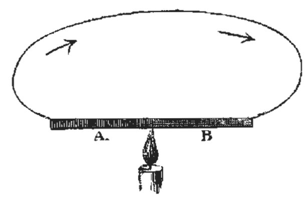


Faraday will study voltaic action extensively in the Seventh Series and will show there its relation to chemical combining power.

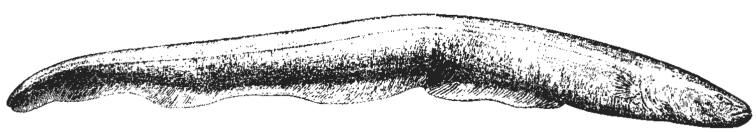
- *Magneto-electricity*, obtained through the relative motion of magnets and conductors, and which Faraday had already studied in the First Series.



- *Thermo-electricity*, produced when the junction between two different metals is exposed to heat.



- *Animal electricity*, which is produced by several fascinating families of both



freshwater and saltwater fishes. Faraday will study the wonderful *electric eel* in the Fifteenth Series, one of the most engaging of all his researches. And, finally...

- *Common* or *ordinary electricity*. This is what we now call “static” electricity: the electricity produced primarily by *friction*—for example, by rubbing a resinous rod with wool, or a glass rod with silk. But how often do we undertake such highly specialized activities as these, except in a classroom or similarly contrived setting? In our day there would seem to be nothing at all “ordinary” about the electricity that arises from friction; but I assure you that when I was a child, rugs, sofas, and especially automobile seats, could easily give you a very unpleasant jolt if you carelessly walked across a carpeted room, or slid out of an upholstered piece of furniture, and then touched a doorknob or a water faucet. Today, many fabrics contain antistatic materials which greatly reduce the frequency of

such experiences; so for us, the terms "common electricity" and "ordinary electricity" are no longer apt, and they are consequently no longer in common use.

Unfortunately, today's more familiar term, "static electricity," is misleading in its own way; for many of the signs that alert us to the presence of static electricity occur precisely when that electricity is *not* static! Those unpleasant shocks which lurked in my family's home and automobile, patiently awaiting their opportunity to strike, represented the *discharge* of electricity which had previously been built up by friction: they were instances of *electricity in motion*, not electricity at rest.

Faraday's efforts to demonstrate the identicality of this "swarm" of electricities occupies the first and longer part of the Third Series. Only then does he set out upon the second part, where the topic is *measure*—and particularly the measure of *quantity*. Readers may notice a distinctive suppleness in the language Faraday adopts for this discussion: while he does not reject the imagery of electric fluids outright, he never crafts his descriptions in a way that *depends* on that imagery.

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Now, one way we can estimate *quantity*—whether of electricity or anything that is *evolved* or *produced*—is to identify a *repetitive element* in the process that produces it; then, presumably, each repetition of that action will produce an equal amount afresh. Faraday obtained common electricity from a frictional "plate machine," in which a large plate of glass was rotated against a fixed "rubber"—which was usually made of silk-wrapped leather, rather than what we now call rubber. The appliance shown here is a smaller version of Faraday's enormous machine, which featured a glass plate of fifty inches diameter—nearly four times as large as this one.[2]

At several points in the Third Series Faraday treats *each turn* of his machine as developing the same quantity of electricity. You can see why such a supposition is reasonable; for it is easy to make sure that all revolutions of the crank are accomplished with uniform effort and speed. And to the extent that individual turns are identical to each other, there is no obvious reason why successive turns would not produce identical results.

[2] Photo courtesy London Science Museum. The glass disk is 35 cm in diameter.

This "same-again" principle of reasoning is familiar to us in other contexts, such as grinding pepper in a mill. Indeed, in the case of grinding we are rewarded with a clear image of "quantity" in the form of a *heap* of the ground substance, as shown here. But when Faraday cranks his plate machine, no "heap" of electricity is produced. Is electricity even the *sort* of thing that possesses "quantity" in the sense of a heap, a pile, or a mound? Once again we are reminded of Socrates' lament to Meno: "If I do not know the 'what' of something, how can I know the 'such' of it?"[3] In our present case, if we do not know the "what" of electricity, is it really meaningful to ask the "how much" of it?

When Faraday remarked that the term *quantity* was "perhaps sufficiently definite as to sense," he meant to acknowledge that we habitually think of "quantity" through images of *accumulation* or *gathering up*. But do not overlook the note of reservation suggested by his word "perhaps." Faraday is far from confident that electricity is really amenable to such imagery. We regularly use such language for electricity without a second thought; but can we point to any body of *experience* that gives real content to that language?

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If electricity does not manifest its quantity directly in experience, might it do so indirectly? Sometimes, for example, we think it natural to express the magnitude of something in terms of the *power it exercises*. Galileo offers a memorable instance in the *Two New Sciences*; Sagredo is speaking:

> "Thus a vast number of ants might carry ashore a ship laden with grain. And since experience shows us daily that one ant can easily carry one grain, and it is clear that the number of grains in the ship is not infinite, but falls below a certain limit, then if you take another number four or six times as great, and if you set to work a corresponding number of ants they will carry the grain ashore and the boat also. It is true that this will call for a prodigious number of ants..."
>
> [67]

That delightful phrase, "a prodigious number of ants," seems to employ the imagery of *number*; but its rhetorical burden is rather the sheer magnitude implied by the ability to move "the grain and the boat also." The phrase expresses *huge undifferentiated totality*, whose greatness is known primarily by *what it can accomplish*. It is an *indirect* representation of quantity.

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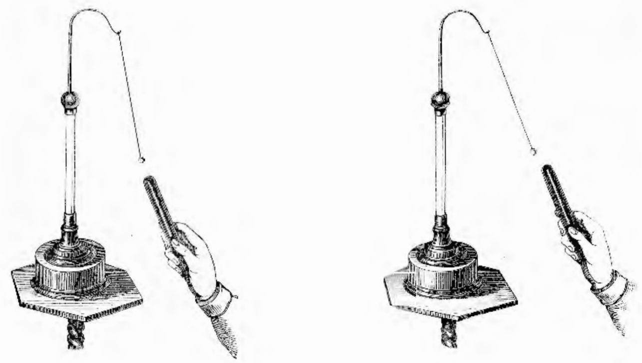
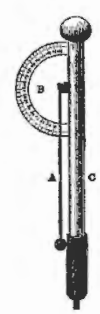
Frictional electricity, too, seems to express *quantity* only indirectly. When a rubber rod is stroked with woolen cloth, it acquires the power to attract a small ball of cork or



pith. We say that the rod has been *electrified*, or *charged with electricity;* and in the left-hand sketch, the electrified rod has succeeded in drawing the ball aside through a moderate angle of perhaps 9 or 10 degrees. But after receiving additional strokes with the wool, the rod is able to urge the ball to a greater angle—perhaps as much as 18 or 20 degrees, as shown on the right. Is it not reasonable to believe that the rod on the right exerts *more attractive force* precisely because it has acquired *more electricity*?

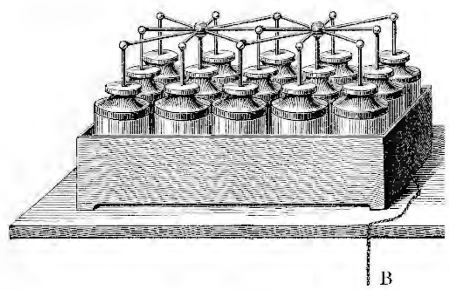
But this is conjecture, not direct experience. Any notion of quantity we can gain from this experiment is limited to what we can surmise from the angle of the suspended pith ball. But *angle* is no image of "muchness," and it shares none of the straightforwardness of such eminently legible figures as *heap*, *mound,* or—in the fluid case—*puddle*.

If not the pith ball, then, might some *other* electrical instrument offer a more immediate experience of electrical "quantity"? The distinctive power of electrified bodies to attract or repel other electrified bodies is the principle of several electric indicators that are considerably more refined than the pith ball. Two early instruments operate on the principle of mutual *repulsion*. The leaves of the *gold-leaf electroscope*, pictured here on the left, diverge from one another more or less,



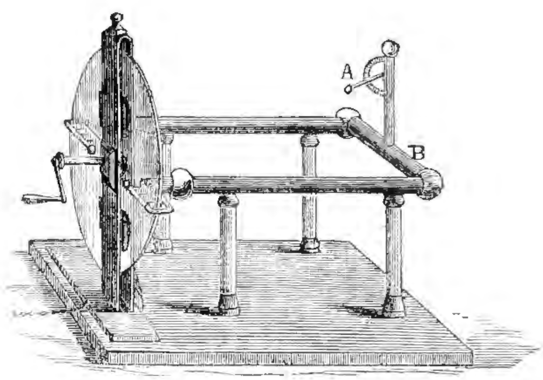
depending, partly, on how many times the rubber rod has been stroked. On the right, *Henley's electrometer* calls even sharper attention to *angle* by incorporating an obvious pointer and protractor in its design; when the instrument is mounted on the electrified conductor of a plate machine like Faraday's, the pointer is repelled from the body, just like the leaves of the electroscope. With its angular scale, the Henley instrument emphatically announces its rhetoric of *numerical measurement*—and hence its name "electro*meter*" rather than "electro*scope*." But *what*, exactly, *does* it measure? The angle of the pointer, even when expressed numerically, still seems far removed from a direct image of *quantity*.

In fact, one of Faraday's experiments in the Third Series suggests that the electrometer is better understood as indicating *some other electrical attribute*—an attribute rather different from quantity, though it may be related to quantity. Faraday describes that experiment in paragraph 363 of the Third Series. It involves an array, or "battery," of fifteen identical Leyden jars, like this one. You see that the central



conductors, which are connected to the jars' inner coatings, are all joined together. Within the wooden container, the outer coatings rest upon a conductive plate that is connected to the flexible chain B, which in turn is connected to the earth.

Faraday will charge these jars using the plate electric machine. Notice the Henley



electrometer mounted on the prime conductor; this was one of the chief applications of the Henley device.

At first Faraday connects only eight of the jars, charging them by thirty turns of the plate machine. This causes the electrometer to rise to some position A. Does that position represent the quantity of electricity supplied to the jars? Certainly that quantity must be considerable, since Faraday noted that merely *one* revolution of the plate will, in his words, "give ten or twelve sparks from the conductors, each an inch in length."[4]

At a later stage of his experiment, Faraday charges *all fifteen jars*, again by thirty turns of the machine. This time, he reports,

> The Henley's electrometer stood not quite half so high as before...

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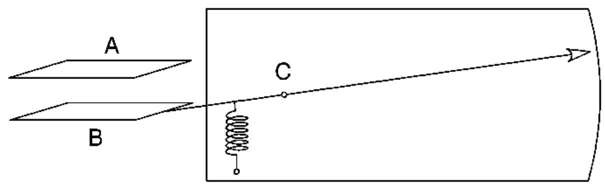
[4] Paragraph 290.

Obviously the electrometer is not measuring quantity! For the quantity of electricity was *the same* in both cases—the result of thirty turns of the machine. Yet with a greater number of jars, the electrometer reading was lower by more than half. What electrical characteristic *was* it, then, that the electrometer measured when it registered that striking reduction?

In hopes of answering this question, let us conduct an experiment of our own. Recall that Faraday noted the generous number of *sparks* produced with each turn of the plate machine. This should give us pause: why does the machine produce a *series of sparks* rather than one continuous spark?

To study the conditions under which spark develops, I will use an electrometer of still greater refinement—one which, although invented long after the Henley device, does not differ greatly from that instrument in the essentials of its operation. The *electrostatic voltmeter* operates on the principle of attraction rather than repulsion. On



the left is a photograph of our meter. It dates from the 1950s, and is therefore calibrated in units whose defining assumptions would have had little meaning to Faraday. But we can regard the scale divisions as *arbitrary units of attractive force*; let me explain this.

On the right is a much-simplified diagram of the meter's internal mechanism. A movable plate B is mounted on a pointer which pivots at C and is held in an equilibrium position by a very light spring. Plate A is fixed in place. When the plates are oppositely electrified, they attract one another; and plate B will move upward until its force of attraction is balanced by the spring. The pointer's angle of displacement then reflects the amount by which the spring has been stretched, and therefore, also, the force of attraction between the plates. The scale divisions are so marked as to represent, broadly, equal increments of that force.[5]

We will connect the electrometer's plates to a Wimshurst machine. I have separated the machine's terminals by about a millimeter or so (VIDEO BEGINS).

[5] This is not really accurate, since true *volt*-meters must take into account both the plate separation and effective plate area, both of which vary as the reading increases. But in the meter we are using, the correction can be ignored for our purposes.

Next, I will slowly crank the machine—and notice that the meter rises until a spark develops, at which point the needle suddenly falls. As I continue to crank, the meter

repeatedly exhibits this pattern of *rise to a maximum*, followed by *abrupt descent* when the spark passes. The maximum is not always the same; but there always *is* a maximum, and the subsequent *descent* always coincides with the *spark*.

The regular association between the meter's descent and the spark suggests a more pointed question: "What is the condition between the terminals *just before* the spark passes?" Whatever that condition is, it evidently results in spark each time it occurs. And since the electrometer consistently develops a maximum reading just prior to each spark, it seems very likely that the electrometer is indicating *precisely that condition* which, when it reaches a certain degree, results in spark. What, then, is the nature of that condition?

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Faraday thought of the spark—and, for that matter, *all* instances of electric discharge—as the *breakdown* of an antecedent *state of stress* in the region where the discharge takes place. Faraday calls that region, or the material which may occupy it, the "dielectric." Here is his description in the Twelfth Series:

> All the effects prior to the discharge are inductive; and the degree of tension which it is necessary to attain before the spark passes is therefore ... a very important point. It is the limit of the influence which the dielectric exerts in resisting discharge; it is a measure, consequently, ... of the intensity of the electric forces in activity.

This golden passage finally lends imaginative content to the term "intensity," which seemed so questionable to Faraday at the outset of the Third Series. The chief manifestation of electrical action is *a condition of tension* in the region between two surfaces, and that action is said to possess *intensity* commensurate with the degree of that tension. "Intensity," then, characterizes the action; "tension" the region or material that experiences that action.

The distinction between intensity and tension is a subtle, but a natural one. We find a comparable distinction in two descriptions of Odysseus' great bow in Book 21 of the *Odyssey*. The suitor Antinous knows the bow in terms of its own *strength*, which makes stringing it so difficult. He warns the crowd:[6]

[6] Homeric passages translated by Gilbert Murray.

> "For not easily, I think, is this polished bow to be strung."
> (line 90)

(The image in this slide is that of a fifth-century Theban coin.) But once the bow *is* strung and in action, it is known by the *thrum of its string*, the sign of surpassing tension:[7]

> And Odysseus held it in his right hand, and tried the string, which sang sweetly beneath his touch... (line 408)

Just as Odysseus' stout bow reveals its strength through the superlative degree of tension it creates in the string, so electric action reveals *its* strength, or *intensity*, in the form of tension in the material between oppositely-charged electrodes. *Intensity* and *tension* are two different rhetorical aspects of electrical action: "intensity" characterizes the action itself (corresponding to the *bow*); "tension" characterizes the material or region which experiences that action (analogous to the bow*string*). Do not underestimate the scientific importance of such metaphorical images as those of string and bow. Without them, or something like them, our understanding of natural powers would degenerate into a merely formal correlation of *numbers* with *numbers*. But any reader of Faraday quickly discovers that Faraday has little interest in symbols, numerical or otherwise. Faraday is constantly alert for *legible images* that convey the essential character of nature's beings and powers. What is so remarkable about Faraday's experimental practice is how much of it consists in allowing the phenomena to *reveal their own images*.[8]

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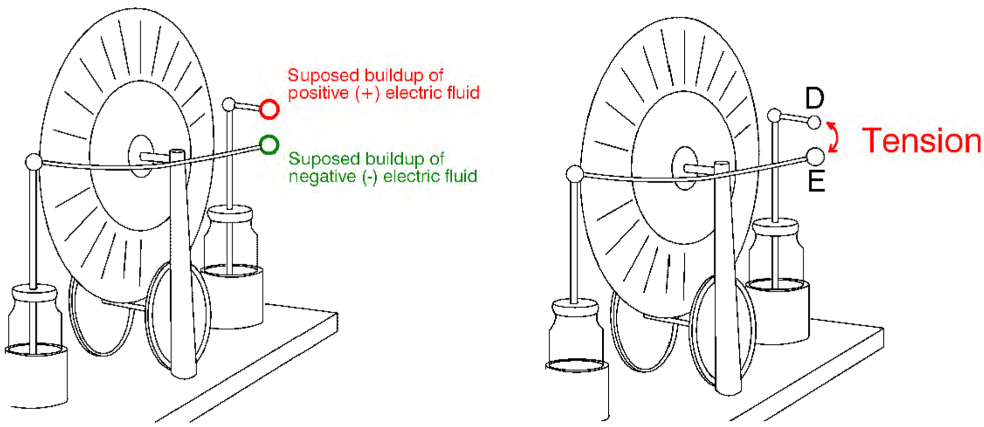
[7] Illustration: detail from an etching by Theodoor van Thulden, part of a series produced in 1632–33.

[8] Fisher, Howard, "The Great Electrical Philosopher," *The College*, XXXI,1 (July 1979).

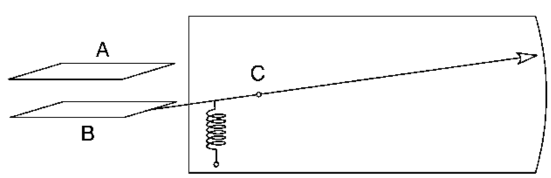
Faraday's interpretation of electrical discharge as being essentially a *release of antecedent tension* departed sharply from the then-accepted account, represented here on the left. Conventional thinking posited a *buildup of opposite electric fluids* on the



surfaces between which spark took place. As those fluids accumulated—or so the account maintained—the inherent repulsion of like portions of fluid, combined with the mutual attraction of unlike portions, would eventually propel the electrical substances across the gap to combine with and nullify one another. Notice that the conventional view recognizes *no role* for the space or material between the charged surfaces; all action is ascribed to the electrical fluids.

Faraday's view—represented on the right—reverses the order of priority by focusing on the *gap* rather than the bodies which it separates, ascribing *tension* to the *gap*, but *assigning no causative role* to the adjoining bodies, nor to any supposed buildup of electricity upon them. If the dielectric material occupying the gap is capable of sustaining high degrees of tension, it constitutes what we call an "insulator"; but all known insulators, including *air*, have a limit to the tension they can sustain, and when this limit is exceeded, they *break down*, electrically speaking. The release of tension associated with that breakdown is *disruptive discharge*, or *spark*. In contrast to insulators, the materials classed as "conductors" are incapable of withstanding any tension at all; they break down under the slightest degree of electrical tension, and the condition of *continuous breakdown under tension* is how Faraday understands "current" in a conductor.

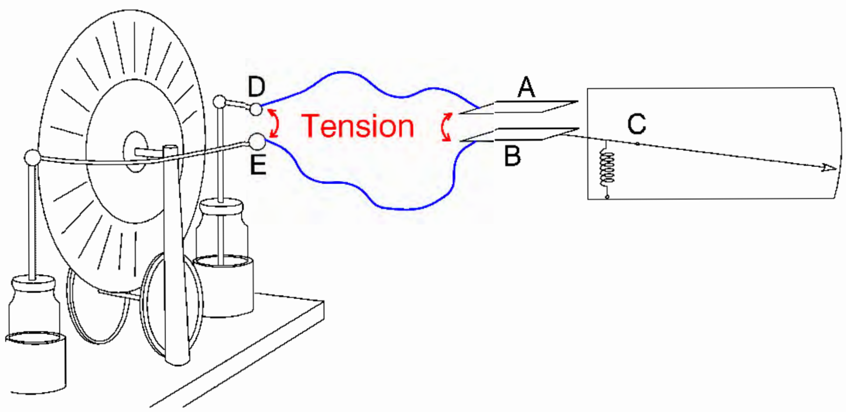
Thus the electrometer's pattern of rise and sudden fall in our spark experiment gives us reason to believe that the electrometer measures that very tension—or its rhetorical counterpart, *intensity*.[9] How does it do so? If you recall our earlier diagram of the electrometer's inner workings, you will remember that the needle's



[9] Throughout the Eleventh and Twelfth Series we find Faraday using the terms "tension" and "intensity" almost synonymously.

displacement indicated the degree of extension of the internal spring, and hence the force on the moving plate—or, rather, the *tension* in the region between the plates. But of course the condition of the electrometer's *own* plates is not what we are interested in! If the electrometer is to function as a measuring instrument, the pointer's displacement must tell us about *some other object*—the object whose condition we wish to measure. How is *that* possible?

Consider, from the standpoint of tension, what must be the case when the electrometer plates are connected to the terminals of the Wimshurst machine. When



the machine is operated, electrical tension is established in the air between its terminals D and E. I say that *equal tension* must therefore develop in the region between the electrometer plates A and B; for if the tensions were not equal, the conductors DA and EB would together have to bear the difference between those tensions. But recall that, for Faraday, a conductor is *incapable* of sustaining electrical tension. Thus the tension between A and B must be equal to the tension between D and E; and the needle's displacement will therefore reflect not only the tension between the electrometer plates but the tension between the Wimshurst terminals as well.

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Have we gained any fuller understanding of those troubling electrical terms, *quantity* and *intensity*? Faraday's study of the forms of electric discharge, especially *spark*, led to the idea of electric tension; and that image of tension, in turn, does indeed seem to offer a firmer notion of *intensity*, namely, *the action producing a certain level of tension* in a dielectric.

But what about *quantity*? Initially, we looked to the *electroscope* as an indicator of quantity; but successive refinements of that instrument brought us, not closer to, but farther and farther away from the expected imagery. All our attempts to find, in experience, the imagery that a material substance would ordinarily demand—a localized heap, mound, or puddle—have led us instead back to *tension*. Why do the phenomena of static electricity seem to lead us so persistently *away* from "heap" imagery and *toward* the vocabulary of tension? Might that be a sign that *tension* is actually more fundamental than *quantity*?

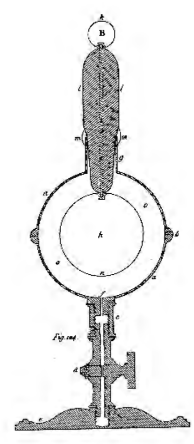
In fact, Faraday already has ample grounds for this view; for if electrifying a body really represents the accumulation of electric substance upon it, we ought to be able to electrify a body “absolutely," that is, *without relation to any other body*—just as we can fill a glass with water regardless of whether or not we fill any other container with water. But Faraday’s famous Cage Experiment, along with other investigations, showed definitively that no body can be in a “charged” condition at all *except through a mediating relation* with some other, oppositely charged, body. This means that there is no such thing as a quantity of electricity *in itself*. Every instance of electric charge is but one element of a mutual relation to which Faraday gives the name “induction”; and in a striking passage in the Eleventh Series he explicitly elevates the *relation* over the *things related*:

> All *charge* is sustained by induction. All phenomena of intensity include the principle of induction ... All *currents* involve previous intensity and therefore previous induction. INDUCTION appears to be the essential function both in the first development and the consequent phenomena of electricity. [1178]

Furthermore, since all of what Faraday calls the “phenomena of intensity” involve *tension in a dielectric*, then it is the *dielectric*, not the so-called “charged” body, which is to be counted as the principal entity in static electricity. In Faraday’s words,

> In the theory of induction founded upon ... action of the dielectric, we have to look to the state of that body principally for the cause and determination of the ... effects. [1368][10]

If the *dielectric* is indeed the principal entity in static electric induction, it is easy to see why Faraday devoted so much of the Eleventh Series to studying the dielectric specifically. To that end, he designed the special “inductive apparatus” illustrated here.



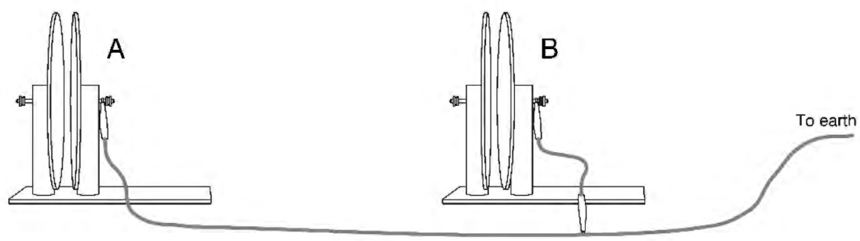
The appliance on the left is an historical reproduction;[11] Faraday’s own diagram appears on the right. Today we would call this contrivance a *spherical capacitor*; but it

[10] In an omitted term Faraday characterizes the action in question as “molecular.” By this he merely means action at the level of *small portions* of the dielectric. He does *not* refer to chemical molecules of the sort propounded by atomic theory—as readers of his 1844 paper, “A Speculation touching Electric Conduction and the Nature of Matter,” will appreciate. See *Experimental Researches in Electricity*, Vol. II (1844), p. 284.

[11] Photograph generously supplied by Dietmar Höttecke; see Höttecke, Dietmar, “How and What Can We Learn From Replicating Historical Experiments? A Case Study.” *Science & Education* **9**, 343–362 (2000).

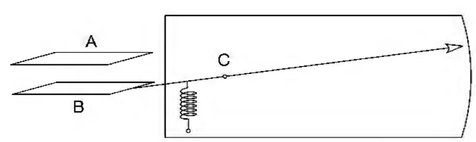
is essentially a Leyden jar consisting of an *outer* and an *inner conductor*, with electrical connection to the inner conductor established by a conductive wire terminating at the little sphere on top. Faraday's experiments established for all time the pre-eminent role of the *dielectric* in induction.

We can emulate Faraday's induction experiments.[12] In place of his spherical capacitors, we shall use a pair of our adjustable plate capacitors, set to equal plate separations and thus electrically identical.



Faraday placed his two identical inductive devices on a grounded metal work surface, so that their outer conductors were permanently connected to the earth while their inner conductors remained free. We will use a heavy copper wire for the same purpose by connecting it to the earth. The righthand plates of our capacitors are joined to it, and are thus in permanent electrical contact. The lefthand plates will be isolated from one another, except when I briefly connect them later.

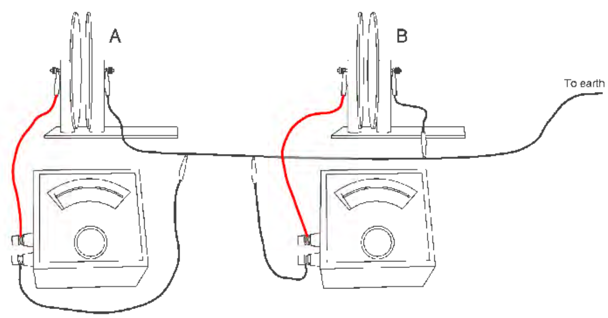
To measure the electrical tension that developed when his devices were charged, Faraday employed a sensitive torsion balance, pictured here on the left. That fine



instrument balanced the tension between two electrified spheres against the elastic twist of a slender thread—just as our modern electrometer, as in the diagram we saw earlier, balances the tension between two electrified plates against the elastic stretch of a spring. Both instruments, therefore, serve to measure electric tension.

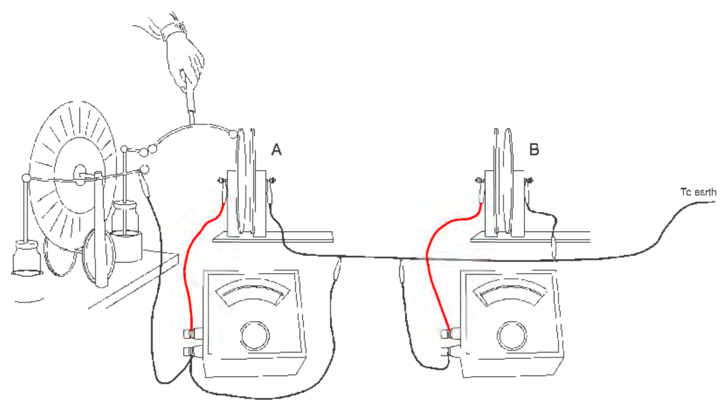
[12] Faraday describes this series of experiments in paragraphs 1208–1214.

Faraday possessed only a single balance with which to measure both his inductive devices; but we have the luxury of using two electrometers, one for each capacitor,



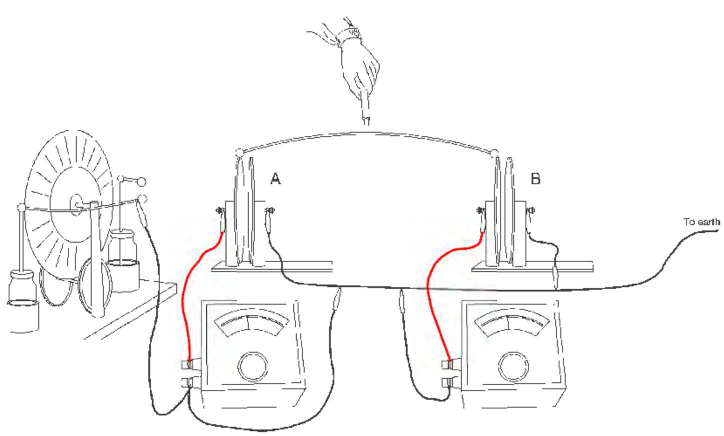
designated A and B, respectively. Let me first outline the procedure we shall be following; then I'll show some videos of the actual experiment.

Faraday began by charging only one of his devices. Similarly, I will connect the Wimshurst machine to capacitor A alone, and crank it until the electrometer

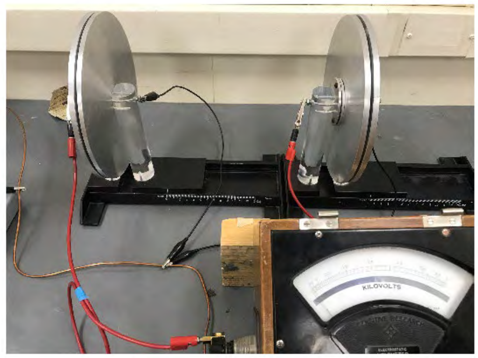


approaches its full scale reading. Capacitor A will thus sustain a definite tension, indicated by the electrometer. Capacitor B, of course, will remain uncharged and will sustain *no* electric tension.

Next I will momentarily join the ungrounded capacitor plates. Now, think about



what must happen when I do that. The joining wire is a good conductor, so it cannot sustain tension; therefore when contact is made, the electrical condition of *both* capacitors should instantly change to make their respective tensions *equal*, and we should expect both electrometers to read the same. That will constitute the first part of our experiment; so now, let us carry out the steps I just described (VIDEO BEGINS).



Here is the setup. The copper wire that is appearing on the left will connect capacitor A to the Wimshurst machine... Now I am cranking the machine, and you can see the electrometer rise almost to its full scale.

And here is a closeup view of the electrometer; it shows that Capacitor A is sustaining a tension of 2.80 units. I could not fit the second electrometer into this view,

but it reads *zero*—as of course it must, since Capacitor B was not charged.

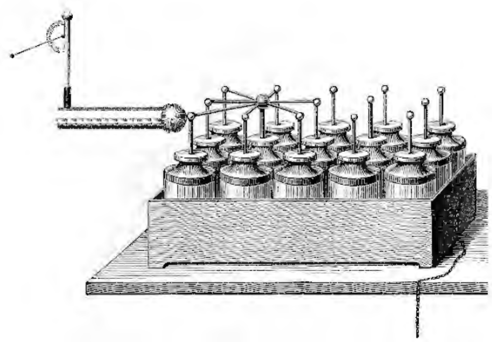
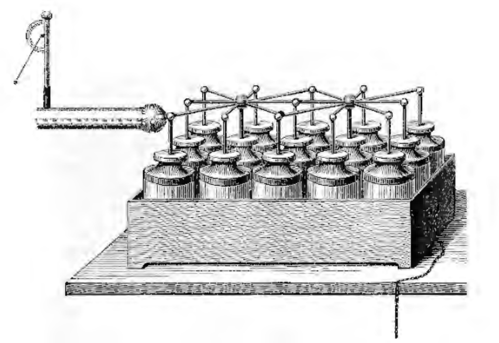
Now I join the capacitors momentarily ... and the tension in Capacitor A *falls*; we'll take a closeup look at the electrometer to see the new value...

The tension in Capacitor A has fallen to 1.37 units, while the tension in Capacitor B has *risen* to the same amount, as it must—though, again, I could not include both meters in the same view.

Now, this change in tension took place when I allowed Capacitor A to share its electricity with Capacitor B. But since the capacitors are *identical*, they ought to divide that electricity *equally*—so that each capacitor should now embrace *half* the quantity of electricity that resided originally in Capacitor A alone.

And the tension in both capacitors is 1.37 units, that is, almost exactly *half the initial tension* of 2.80 units. Thus as the *quantity of electricity* in Capacitor A diminished to half, so too its *tension* diminished to half. Evidently *tension is here proportional to* *quantity!* But doesn't this contradict what we saw in the Third Series? For there, when Faraday charged first eight Leyden jars, and then fifteen, with the same quantity of electricity, his Henley electrometer gave two different readings; and obviously if one magnitude can take on two different values while the other remains unchanged, those magnitudes cannot be proportional.

This reasoning, though, overlooks a critical difference between the two experiments. In the Third Series, Faraday was comparing the tension of a *fixed quantity* of electricity distributed first over eight jars and then over fifteen jars, as illustrated here. The electrometer readings are indeed very different, just as Faraday reported.

But our experiment, like Faraday's in the Eleventh Series, compares the tensions of *different* quantities of electricity in *one and the same capacitor*. The two experiments are not comparable, because in the earlier exercise the physical environment underwent significant change—from a smaller number to a greater number of jars—while in the later experiment the environment did *not* change: the electrometer measured the variation of tension in *one and the same* capacitor.

Clearly, the *physical environment* affects how much tension a given quantity of electricity will develop. This should not surprise us, since that environment includes the *dielectric;* and we have already seen how central is the role of the dielectric, according to Faraday's thinking.

The next step in Faraday's experiment, and in ours, will confirm that central role by showing that different dielectric materials develop specifically different tensions. Faraday filled the air space in one of his devices with various substances; and we shall do the same to our capacitor B by inserting a sheet of glass between its plates. Then we will run through the same experimental sequence as before; but remember that this time, our capacitors will no longer be identical.

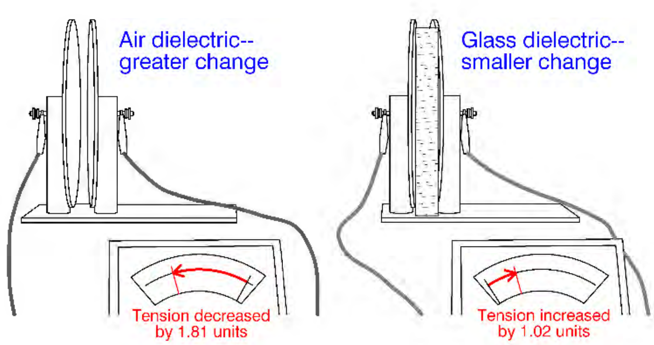
(VIDEO BEGINS.) You see I have mounted a glass sheet between the plates of Capacitor B.

And again we connect Capacitor A to the Wimshurst machine, and charge it to an initial tension.... Its electrometer reads 2.83 units, nearly the same as before, while of course the other electrometer continues to read *zero*.

Again I briefly join the two capacitors together; and the electrometers once more display equal deflections—as they must, since the tensions have to be equal. But notice that this time the tension is not equal to half the original tension... Instead the tension is only 1.02 units, roughly *one-third* of the initial tension. How shall we understand this?

When Faraday obtained a similar result with his spherical capacitors, he concluded that the apparatus containing a solid dielectric had, in his words, "a greater aptness or capacity for induction" than the apparatus whose dielectric was *air*. To see what he means by this phrase, let us analyze our results in the same way that Faraday interpreted his. When I joined the two devices, the charged capacitor gave some of its electricity to the uncharged capacitor. Specifically,:

- The capacitor with air dielectric lost a certain quantity of electricity, and its tension decreased by 1.81 units.
- The capacitor with glass dielectric gained that same quantity of electricity, but its tension increased by only 1.02 units—a much smaller amount.



- Thus one and the same quantity of electricity is associated with *lower tension* when the dielectric is glass, and *higher tension* when the dielectric is air.

Evidently, then, "greater capacity for induction" means the ability to sustain the same quantity of electricity at a lower tension. Or, equivalently, it denotes the ability to sustain a *greater* quantity of electricity at *the same* tension.

We could go on, as Faraday does, to show that a dielectric's "capacity for induction" depends on its *dimensions* as well as its specific material. But the main point is clear: where static electricity is concerned, our only access to electrical "quantity" is indirect—through the measurement of tension,[13] taking account of the medium's capacity for induction. And thus we must regard electrical quantity as only an alternative rhetorical expression for tension—a *special figure of speech*. Recall Faraday's earlier remark, that we have to look principally to the *state of the dielectric* for the determination of the electric effects. In contrast, he described the supposedly "charged" conductors in this almost dismissive way:

> The conductors ... may be considered as the termini of the inductive action.... [1361]

Charged bodies, then, are merely the *boundaries* of electrical action, not its cause! To say that a body is "charged" no longer labels it as the *source* of electric effects, but merely the place where a medium that *does* sustain tension switches to a medium that does *not*. With this characterization, Faraday has effectively turned the conventional order of causal priority on its head. *Charge* is no longer prior to *tension*; rather, *tension* is prior to *charge*. Whatever else this may mean, it fatally undercuts the notion that "charge" is the name of an electrical substance, for—to use an Aristotelian formulation that would have been quite foreign to Faraday: "How can a non-substance be prior to a substance?"[14]

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I hope I have conveyed how thoroughly Faraday's account of electricity inverted the conventional understanding. At the same time, I hope it is clear that Faraday did not arrive at his unorthodox view through polemic or disputation. He did not marshal evidence so as to *refute* the established conceptual scheme. In fact, at least in the *Experimental Researches*, Faraday hardly ever engages in "collecting evidence," any more than he engages in symbolic mathematics. Instead, he looks directly to *nature showing itself*.

Classic doctrines of scientific "method" emphasize putting hypotheses and conjectures to the test, establishing a preponderance of evidence for or against them.

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[13] For electricity undergoing *discharge*, as Faraday shows, the ballistic galvanometer offers an alternative measure of quantity. But while it might seem obvious that when electricity discharges, its quantity in discharge must be the same as its quantity *prior* to discharge—when it was still static—the problem of correlating the measures of *static* and *dynamic* electricity would prove to be a knotty one. It would eventually become the problem of relating the *electrostatic unit* to the *electromagnetic unit*, the problem that would lead Maxwell to his electromagnetic theory of light.

[14] Aristotle, *Physics*, Book I (189a34) tr. Cornford. In the present case, how can *tension* (not a substance) be prior to *electric fluid* (a substance)?—implying that electric "fluid" is not actually a substance after all.

Such an approach is suited to an *alien* world, a world indifferent to human understanding, a world in which, as has been said, "nature loves to hide."[15] Faraday's world, on the contrary, shows itself in forms that may *challenge* our understanding; but they are not *incommensurable* with it. Faraday's science flourishes in a world that is *fit* for us, a world that is preeminently knowable.

How did Faraday manage to nourish a scientific outlook so little influenced by conventional scientific doctrine? A customary answer to this question singles out Faraday's lack of a conventional education. To be sure, Faraday had little formal education and was largely self-taught; but the *materials* of his self-education were steeped in established knowledge. As a bookbinder's apprentice, he read volumes of the *Encyclopædia Britannica* while engaged in binding them. By his own account he benefited greatly from Jane Marcet's *Conversations in Chemistry*, a lovely book which, however, reliably held to established and accepted teachings.[16] Through the generosity of a friend of his employer, Faraday was able to attend lectures by Humphrey Davy, an establishment figure in science if there ever was one. I do not think it was ignorance of established science that explains Faraday's relative indifference to it. Much of his practice in "reading the book of nature"[17] points instead to his religious tradition.

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Faraday belonged to a very small Christian denomination, the Sandemanians, a dissenting offshoot of the Church of Scotland. Sandemanians eschewed theology and had no established clergy; instead, the Bible was the central source of guidance in every aspect of their lives. Reading the Bible demanded no special credentials, for it was written in human language for the sake of human understanding.[18] Similarly, they saw the natural world as having been created as a gift and a fitting home for mankind. Like the biblical text itself, the created world was seen as a channel of God's communication with the human race.

You can see how such views concerning nature could inform Faraday's methods of natural investigation. If natural phenomena show themselves in terms we can grasp, they will not need to be expressed mathematically—or, for that matter, through any other external symbology. We see from Faraday's own example that the study of nature requires patient and prolonged labor—but much of that labor stems not from nature's recalcitrance but from our own sluggishness to put familiar thought patterns aside—what Faraday once called "mental inertia"[19]—and allow the phenomena to speak to us directly. For Faraday, at least, the means for cultivating an ear for nature's

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[15] Heraclitus, B123

[16] Jane Marcet never sought to break new scientific ground; but by composing instructional texts that were explicitly directed to young women, she conspicuously broke new social and educational ground.

[17] Geoffrey N. Cantor, "Reading the Book of Nature: The relation between Faraday's Religion and his Science" in *Faraday Rediscovered: Essays on the Life and Work of Michael Faraday, 1791–1867*. The Macmillan Press, Ltd. (1985).

[18] See David Gooding, *Michael Faraday, 1791–1867: Artisan of Ideas*. http://www.bath.ac.uk/~hssdcg/Michael_Faraday.html, 15 June 2002; accessed 4 September 2023 through the Wayback Machine.

[19] See Faraday's "Observations on Mental Education" (1854) in *Experimental Researches in Chemistry and Physics* (1859), p. 463

dialect and an eye for its forms are *practical* rather than analytical. Before he asks questions in speech, he asks them in practice; such are Faraday's experiments.

Nevertheless, while Faraday's mode of experimenting clearly reflects central elements of the Sandemanian outlook, it would be a mistake see him only as dutifully putting the Sandemanian creed into action. Faraday just doesn't write as though he were feeling the weight of doctrinal obligation. His prose, both in his laboratory *Diary* and in the published *Researches*, is simply too fresh, too lively, too responsive to *what just happened*. There is a palpable difference between *being open to nature* and *observing a code* of being open to nature. I invite you to think about that difference—the difference between *responsiveness* and *responsibility*[20]—and how it plays out both in consciousness and in speech. But for now let us return to the terms "quantity" and "intensity," the two candidates for electrical measure; for as regards their lucidity, I think we will have to acknowledge that the terms have effectively exchanged places.

The term *intensity*, which Faraday initially found "more difficult to define," has gained considerable clarity, since Faraday has been able to assimilate to it the figures of speech associated with *tension*; and we may now understand electrical intensity as commensurate with the *degree of tension* developed in a specified region. But the term *quantity*, which Faraday previously thought "sufficiently definite as to sense" has instead become highly questionable. For the "definite sense" of that term rested on the image of *heaping up* or *accumulation* of electrical substance; and we have seen how that image has repeatedly failed to find any grounding in experience. Moreover, now that Faraday has identified the primary electrical entity as being the *dielectric under tension*, not the so-called *charged body*, any idea of "quantity of electric substance" can only be regarded as a merely verbal one—a figure of speech. Under such circumstances, would it not behoove any responsible thinker to avoid the term "quantity of electricity" altogether? And yet Faraday continues to speak of "quantity of electricity" throughout the remainder of the Eleventh Series, and in the Twelfth, Thirteenth, and Fifteenth Series. Why would he do this?

Faraday nowhere speaks directly to that question as regards electrical terminology; but he does address a similar one in connection with the language of *atoms*. Some of you have read, and some of you will read, his 1844 paper, "A Speculation touching Electric Conduction and the Nature of Matter."[21] In that essay, after having reviewed his many reservations about the theory of atoms, and hence also the atomic language that takes their existence for granted, he nevertheless admits,

> I feel myself constrained, for the present hypothetically, to admit them [that is, *atoms*], and cannot do without them.

Here, then, is another instance where Faraday feels obliged to make at least provisional use of a terminology that has not been grounded in phenomena. A doctrinaire purist would have avoided such a compromise; but Faraday's openness

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[20] Contrast, for example the Knight of Faith in Kierkegaard's *Fear and Trembling* with the rule-inferring "insomniac" who, reflecting on Abraham's willingness to sacrifice Isaac, confidently deduces, "Oh, I see how it works: you raise the knife, and then suddenly there's a ram!"

[21] *Experimental Researches in Electricity*, Vol. II (1844), p. 284, esp. page 289.

extends to language as well as to experience, for each of these must evolve along with the other.

Natural phenomena show themselves in forms and images that human beings can apprehend; and those images continually try to shape a language that is anchored in the phenomena. But such a language requires discovery, interpretation, and adeptness; and these in turn require time, patience, and love. As we do not expect to take in a dialogue, or a drama, on first reading, we must not expect to "perform" experiments once only and then set them aside. We must live with them, enter into them, and try them again and again. The idea is less to get the right answer, than to capture the right idiom. The book of nature deserves multiple readings; and no two of those readings are likely to be quite the same.