If the quantity in a region be increased by increasing the conducting power, the needle will show no such increase; on the contrary, it will indicate *diminution* of force, because the tension is diminished; or if the quantity be diminished by diminishing the conducting power, it will show *increased* force. The force might even lose in quantity and gain in tension in such proportions that the needle should show no change; or it might gain in quantity and lose in tension, and the needle still be entirely indifferent to the whole result.

2871. If my view be correct, then the magnet is not, as at present applied, a perfect measure of the earth's magnetic force...

* * *

Royal Institution
September 14, 1850

2870, continued. *If the quantity in a region be increased by increasing the conducting power...*: This is the third case—increased quantity and constant tension (but see the next two comments). If the inductive capacity of a dielectric is increased, it will support a greater quantity of electric induction at the same tension as before (paragraph 1214, *comment*). The same relation will hold, analogously, for magnetic quantity, tension, and conducting power.

the needle ... will indicate diminution of force...: Again we know experimentally that when a paramagnetic body is immersed in a more highly conductive medium it responds less energetically to magnetic action. Or in terms of Faraday's earlier explanation, when the medium becomes more conductive, some lines of force that were previously carried on by the magnetic needle become rerouted through the medium instead; thus the needle's responses are correspondingly weakened.

...because the tension is diminished: This claim is confusing since, as we have just seen, the needle's diminished action does *not* presuppose reduced tension. Moreover, if the cases being considered are to illustrate how "the tension can change whilst the quantity remains the same, and the quantity can be altered, yet the tension remain unaffected," then the third case should be one of *constant*, not diminished, tension. It is certainly *possible* for magnetic quantity to increase while magnetic tension decreases—it requires only a sufficient increase in magnetic conducting power of the medium—but Faraday should not have asserted categorically that the third example constitutes such a case.

2871. *the magnet is not ... a perfect measure of the earth's magnetic force*: Since Faraday is discussing terrestrial magnetism, he mentions the earth's magnetic force specifically. But the magnetic needle's deficiencies limit its performance in *any* magnetic measurement.

Twenty-Eighth Series — Editor's Introduction

The Twenty-eighth Series begins a climactic stage in the Experimental Researches, in which the character and distribution of magnetic power will exhibit itself with unparalleled access and intelligibility. In a pair of breathtakingly beautiful exercises Faraday will demonstrate, first, how to *count* magnetic lines of force and, second, how to determine their distribution experimentally, not only in the regions surrounding a magnet but actually *inside* it! But of course those procedures are only as significant as the lines of force themselves. So before taking up any other topic, Faraday stops to review and justify his continuing employment of the lines of force as meaningful, accurate, and competent representatives of the magnetic power.

What is a line of force?

As he opens the Series Faraday acknowledges having made repeated appeal to "lines of force" without, up to now, stating clearly what they are, what formal properties they possess, and how literally we are to take them. Although it seems clear that Faraday himself is prepared to view them as highly concrete, he recognizes that some investigators may prefer to consider the lines of force solely in their representative capacity, as symbolic constructs that facilitate our thinking about magnetic and electric powers while making no claim to provide a literal delineation of those powers. Even in so limited a role, he urges, lines of force have many advantages over rival descriptive vocabularies, such as those which invoke "poles" and "fluids". Nevertheless, he warns, we should not overlook the far greater significance which lines of force may possess. For it is at least possible that in lines of force we are quite literally observing *powers made visible*—just as his "paradigm" for science (for so I characterized his opening footnote in the Nineteenth Series*) earlier prescribed.

We have seen already how many electrical and magnetic phenomena seem to imply a certain connectedness in things, a pattern of successive and progressive transmission of activity from the agent to the site of action. Such communication is a *physical* process; and if the lines of force do indeed exhibit it directly, they must themselves possess some sort of physical status. What, then, will lines of force be if they are "physical?" It is easier to say what they will *not* be. Lines of force will not be mathematical constructs, not hypothetical, not merely symbolic. They will be natural, corporeal beings—as are rocks, rivers, plants and animals, clouds, stars and planets.

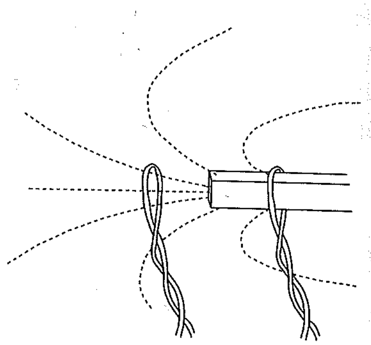
* See also the editor's introduction to that Series.

What then are lines of force? For the present Faraday does not attempt a definitive answer. It is clear that he takes their possible physicality very seriously, but for now he merely advocates their more frequent employment as symbolic devices. He will take a stronger position, though, in a subsequent essay. Its title—*On the Physical Character of the Lines of Magnetic Force*—states clearly enough what that position will be.

The Moving Wire

"The Moving Wire" is Faraday's name for a device, or class of devices, which reveal magnetic lines of force by means of the currents developed in moving conductors. You will of course recall his experiments with moving conductors in the first two Series, long before he began to employ the Line of Force as an interpretive image. Now his return to that inquiry features a series of exercises that depend upon the image of the line of force for their very design. Here is one of them.

A wire loop or ring is connected to a galvanometer. When thrust over the end of a bar magnet it "cuts" lines of force—which emerge in all radial directions from the end of the bar. The galvanometer registers a forward deflection when the ring is placed over the magnet, a reverse deflection when it is removed. Thus each time the loop is placed over the magnet, it will cut the very same lines of force; and it will develop the same quantity of electricity in its circuit.



Now as we saw in earlier Series, a ballistic galvanometer will register this quantity of electricity, provided that the electricity fully completes its action before the (slow-moving) galvanometer needle has departed very far from its original position. For then the needle will be hurled to a maximum deflection, or "throw", proportional to the total electricity evolved. Suppose, then, the ring is placed successively once, twice, three times over the magnet, always well within the period of a single galvanometer throw. And let the galvanometer be connected during each placing of the loop, and disconnected during each withdrawal, so that only the forward currents pass through it. Faraday finds that the galvanometer deflections stand in the same proportion as the respective number of placements—that is, *in proportion to the number of lines of force cut.* He writes (paragraph 3086):

> [W]hen the bend of the wires was formed into a loop, and that carried once over the pole of the [magnet], the galvanometer needle was deflected two degrees or more. The vibration of the needle was slow, and it was easy therefore to reiterate this action five or six times, or oftener, breaking and making contact with the galvanometer at right intervals, so as to combine the effect of like induced currents; and then a deflection of 10° or 15° on either side of zero could be readily obtained.

As a trial of proportionality, the results cited here are admittedly pretty rough: A figure of "two degrees or more," multiplied "five or six times" can only charitably be reckoned equal to "10° or 15°". But quantitative confirmation of the proportion is not Faraday's aim in this first exercise—a succession of increasingly more sophisticated measurements throughout this Series and the next will accomplish that. Rather, the loop procedure marks the beginning of a profound *transformation* which the Moving Wire is about to undergo.

When Faraday first announced *magneto-electric induction,* the evolution of currents in a moving wire was the very nucleus of the phenomenon, and a central focus of the overall investigation. But in the present Series Faraday reasons, from those very currents, to the *quantity* and *disposition* of the magnetic power that induced them. The Moving Wire is thus transformed from a *phenomenon* in its own right into an *instrument* by which other phenomena are themselves disclosed and interpreted.

We have seen this sort of metamorphosis before. Oersted's observation, that a compass needle was deflected in the vicinity of a current-carrying wire,* was initially a marvel and a wonder, itself the subject of extensive and vigorous investigation. But as the Experimental Researches begins, that effect has already been converted into a principle of measurement, habitually and routinely applied in the form of the *galvanometer*—that workhorse of the electrical laboratory.

The "counting" principle

The loop exercise, then, shows a rough proportionality between the *quantity of electricity evolved in,* and the *number of lines of force cut by,* the Moving Wire. As the Series progresses, Faraday will alternate between assuming that relation and confirming it more precisely. The proportionality becomes a powerful principle of *counting* because it permits him, from the quantities of electricity evolved in the circuit and

* Described in the editor's introduction to the First Series.

measured by the galvanometer, to calculate the relative number of magnetic lines of force that traverse any area the moving wire can be made to sweep out.*

The instrumental significance of this proportionality is great indeed. Nevertheless, Faraday is less interested in *proportional magnitudes* than in the *meaning of proportionality*. In his eyes the "counting" principle is much more than a new and powerful measurement technique—it reveals the germ of a new image of the magnet. For if a quantity of electrical action is strictly proportional to a quantity of magnetic lines, then *each line* may be accounted responsible for a determinate share of the total effect; and the magnetic lines of force are confirmed as *agents*, each embodying a determinate power.

The "counting" principle thus has interpretive as well as instrumental significance. Faraday will explore both of its aspects in experiments with a rotating magnet—a theme which, if you recall, marks another return to an early Series (paragraphs 218–220).

The rotating magnet

Faraday has an ingenious device which permits him to study a rotating magnet with the moving wire. His description of the apparatus is a model of clarity, and he recounts the individual exercises in full. Yet he touches upon their consequences with such delicacy that readers sometimes overlook their collective significance. It may be helpful, then, to summarize the experimental results in advance. I see them as threefold:

1. *Disposition of the lines.* The rotation experiments will establish the existence of lines of force *within* the magnet, identical in nature to those external to it, equal to them in number, and continuous with them in direction. In other words, the lines of force of a common magnet will be revealed as *closed curves*, neither arising nor terminating at the body of the magnet.

This is indeed a momentous result; for it removes at one stroke any visual imagery, at least, of "poles" or "magnetic fluids" or any supposed fountain of creation from which the lines of force might be imagined to pour out. In the absence of terminations, *any* point on the line of force is as strong a candidate for being the line's "origin" as any other point; so postulating a "pole" or a puddle of "fluid" at some location on the line becomes instantly futile.

* Recall that an independent *quantitative* measure is just what has been lacking for *electric* lines of force; see the comment to paragraph 1378 and the Twelfth Series' introduction.

2. *Force of the lines.* The experiments will establish that one line of force represents the same *quantity* of force (power, action) at every location—regardless of the line's angle, direction, or curvature; or its distance from any object; or its convergence towards or divergence from neighboring lines of force. When Faraday proposed a similar idea for electric lines in the Twelfth Series (paragraph 1369), he could offer it only as an interpretive rule. Now he has strict experimental demonstration of the principle, at least for magnetic lines.

3. *The role of iron and air in a magnet.* The iron interior of a magnet, and the air (or other exterior medium), sustain *equal power* since the same lines of force pass through both. They are moreover *equally essential* to the magnet, since a closed line of force cannot be sustained in one medium without passing through the other as well. Finally, the lines of force appear to have the same mode of existence in one medium as in the other. To use the language of the 26th Series, the media are merely unequal in conducting power—they differ in degree, not in kind. But this overthrows our conventional notion that the iron *owns* the lines of force, so to speak—that the iron *is* the magnet, while the surrounding air is only the incidental environment in which it happens to have been placed. Can we then, in any sense, continue to regard the magnetic power as "belonging" to the iron?

Considerations such as these make it harder and harder to distinguish "inner" from "outer" with respect to the magnet—or even to differentiate one magnetic medium from another. Eventually, I believe, they will cause Faraday to moderate somewhat that absolutism regarding matter and space he expressed in an earlier Series.* He will express such moderation overtly in later papers; but since the rotating magnet experiments of the present Series mark the real inauguration of that more temperate view, I call attention to it now.

* See the Twenty-sixth Series' introduction.