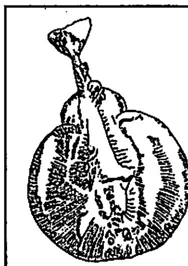
FARADAY'S ELECTRIC EEL
Part I: The Body Electric[1]

I
Does the electric eel shock itself?


Slide 1

In the dialogue *Meno*, that otherwise unmemorable character establishes his own lasting memorial by creating one of the most memorable similes in all the dialogues: Socrates, he says, is like the *torpedo-fish* [SLIDE 1] whose shock plunges his prey into a stupid paralysis. Meno calls the simile his "little jest"; and while Socrates agrees to accept the supposedly playful image, he makes an important qualification:

> If the torpedo torpifies itself while making others torpid, then I may be compared with it; otherwise not.

Torpidity in the fish's victim represents the perplexity and ineptitude displayed by one who, like Meno, has been forced under Socratic questioning to acknowledge his own ignorance. Thus the turn Socrates gives to Meno's simile means, first of all, that Socrates paralyzes his respondents not through mastery but through deficiency—through the same mortal ignorance that Meno has been brought painfully to face in himself.

But scarcely concealed beneath Meno's jocularity—by this time turned rather brittle—lies a more disturbing element. Meno's caricature of Socrates is rife with allusions to the occult and supernatural. He declares that Socrates is "bewitching" him with "spells and incantations," and that in any other city Socrates would be condemned as a "wizard." This more sinister theme casts Socrates as other-worldly, with an inhuman and perhaps unnatural power over men, as the weird powers of the torpedo-fish set it apart from more conventional carnivores. Socrates' correction of the simile thus has a second meaning also: If the torpedo-fish is subject to the very power it itself exercises, then the fish is part of the natural order; and its power is likewise a natural, not a magical one. Similarly, the Socratic power that derives from *knowing that one does not know*—a power to neutralize conventional opinions and break their merely habitual hold over us—will be a human, not a diabolical, power. So much so, for Socrates, that to love wisdom rather than dogma, to be *philos sophoi,* is to exercise the very paradigm of human powers.

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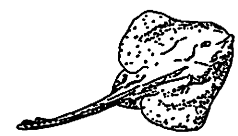
[1] This talk was presented in Annapolis in October 1991 and in Santa Fe on March 29, 2006. An expanded version was published in *The St. John's Review*, XLI,1 (1992) Part Two—"An Undulatory Life"—is scheduled to be delivered in Santa Fe on April 26, 2006.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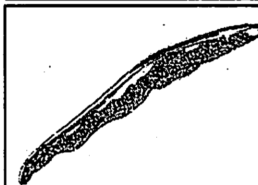
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But *does* the torpedo-fish torpify itself? Is the creature an exemplar of *diabolical power,* as in Meno's simile, or of *activity according to nature,* as in Socrates'? And we might frame a similar question about any of the other animal species with well-developed electric organs who hunt their prey seemingly Zeus-like, hurling down potent electric blasts upon their doomed victims—[SLIDE 2] the *Raia* or electric skate, [SLIDE 3] the *Malapterurus* or electric catfish, and [SLIDE 4] the *Gymnotus* or so-called 'electric eel'. *Does the electric eel shock itself?* That is the question we shall regard as having been suggested by Meno's simile and Socrates' reply. But it reflects a larger question: What is the relation in nature between an agent and its own power?

In November of 1838 Michael Faraday, the great experimentalist and natural philosopher, reported to the Royal Society on "the character and direction of the electric force of the Gymnotus". Faraday had long been trying to obtain an electric eel [1752][2], and in August of 1838 a certain intrepid Mr. Porter succeeded in bringing one to London from South America, where it had been captured five months before. Porter sold the creature to an establishment in Adelaide Street whose proprietors generously made it available to Faraday for such scientific researches as should be consistent with—I quote—"a regard for its life and health." [1754].

This was not Faraday's first encounter with animal electricity. He had in 1833, some five years before, established the probable identicality of all forms of electricity, including animal electricity; and in 1814–15 he had assisted Humphrey Davy in tests, at that time inconclusive, to see whether the shock of the "electric fish" could decompose water.

Faraday's reports to the Society from November 1831 on, along with other writings, were republished by him in the collection called *Experimental Researches in Electricity,* a project that was to grow to three sizeable volumes by 1855. The *Experimental Researches* is a remarkable, highly dialectical book in which, just as in a conversation, topics arise again and again, often appearing in new and surprising forms, and seldom failing to illuminate other, at first seemingly dis'parate, investigations.

Faraday's 1838 Gymnotus report makes up the Fifteenth Series of these Experimental Researches; and I am delighted to be able to say that in it, Faraday actually touches on our question—whether the electric eel shocks itself. True, he mentions it only in passing, and his answer—that "the animal does not apparently feel the electric sensation which he causes in those around him" [1772]—is only a guess. But it is rather

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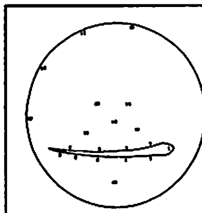
[2] Bracketed numbers refer to numbered paragraphs in the *Experimental Researches.*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charming that Faraday should raise the question at all. Indeed the entire Gymnotus report is charming, with its description of the fish and its history, its inclusion of part of a letter from Humboldt on proper care and feeding ("cooked meat, *not salted*"), and even [SLIDE 5] this delightful sketch, which we shall return to later, of the Gymnotus in his tub.

Repeatedly in Faraday's report we find signs of a wondering and appreciative eye for the striking and exotic in nature. Faraday calls the Gymnotus "this wonderful animal" [1769]; and the word "wonderful" actually begins the paper. But what is the source of Faraday's wonder, in which presumably we too are to share? Is it exclusively the animal's strangeness and mystery—that, as Meno intimates, it goes somehow beyond the bounds of ordinary nature? Or is Faraday capable, and are we, of bestowing wonder on other than the spectacular and the arcane? Faraday characterizes the wonder *he* has in mind at the outset of his paper:

> Wonderful as are the laws and phenomena of electricity when made evident to us in inorganic or dead matter, their interest can bear scarcely any comparison with that which attaches to the same force when connected with the nervous system and with life... [1749]

Clearly the interest raised by animal electricity is not that it goes *beyond* nature. Rather what is compelling here is precisely the *conformity* between Gymnotus' living power and the more prosaic electrical phenomena associated with inorganic bodies. Electrical powers formerly thought to be confined to inert matter are here seen to be exercised by living beings also. Such a communion of powers holds promise for the expansion of our existing knowledge—a promise Faraday is all the more keen to recognize because its importance has not been widely appreciated:

> [T]hough the obscurity which for the present surrounds the subject may for a time also veil its importance, every advance in our knowledge of this mighty power in relation to inert things, helps to dissipate that obscurity, and to set forth more prominently the surpassing interest of this very high branch of Physical Philosophy. [1749]

This is a statement about the order of discovery in nature. Faraday here notes that advances in our understanding of *inorganic* powers will shed light in turn upon *living* processes. Later in the paragraph, Faraday will voice his belief that we are—quote—"upon the threshold of what man is permitted to know of this matter." I take seriously the qualification: *permitted* to know. The promise of animal electricity has nothing to do with forbidden knowledge, wizardry, or things unnatural. Faraday seems to affirm that, just as inorganic forces lie well within the domain of standard science, so an understanding of living forces stands as a merely more distant, but assured, prize.

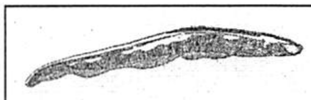
Yet Faraday's mention of the "surpassing interest" of animal electricity presents animal processes as more than mere extensions of inorganic ones. "Surpassing" interest may even suggest a reverse order of discovery: that exercise of a power by a living being might prove to be visible and intelligible in ways that power exercised by inert matter alone is not, and thus may be capable of revealing inorganic forces more adequately than they can reveal themselves. I see two areas in particular where animal electricity might prove to be especially illuminating.

First, in animal electricity we have an instance of *one identical power* exercised both by living and nonliving agents. The baffling relation between an agent and the power it exercises may be more accessible when it is viewed in the comparison between a living and a non-living system; and if so, knowledge of the animal may contribute as much to our knowledge of the inorganic system, as the other way around.

Second, a living creature's ability to respond to and alter its environment *by intention or habit* adds a new interpretive dimension to the animal's electrical relations with its surroundings. The general relation between an agent and its surrounding medium may therefore stand forth more pointedly when exemplified by a living agent. In fact I will argue that the *electric fish* does become for Faraday an explanatory image for inorganic agents, and particularly for the *magnet.*

If the new knowledge intimated by animal electricity is not, as I said, an uncovering of things hidden and forbidden, it must be a knowledge of things which are already there to be seen, but which we have not yet learned to see. Knowledge of this sort will therefore in large measure consist not in the content but in the mode of vision, or one might say, in *rightness of vision.* In the case of Gymnotus, gaining such orthoscopy begins with the quest for an adequate image of the fish himself. Much of Faraday's activity in the Fifteenth Series is concerned with bringing this image to light. Faraday's experiments with Gymnotus are as much concerned with eliciting images of the animal as with establishing factual information about him.

Besides Faraday's own experiments, conventional anatomy plays a role in originating the elements of the Gymnotus images. For example, Faraday is aware that the electric organ tissues are of muscular derivation; he cites Geoffroy St. Hilaire, who classifies them not with the organs of higher life functions but among "the common teguments" [1789]. What this means is that the fish's electric apparatus is comparable in its office to any of the ordinary muscular organs, for example to the locomotory structures, the *fins.*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Gymnotus' anal fin, [SLIDE 8] which runs some 4/5 the length of the body, is that animal's principal locomotory organ. The fish propels itself forward or backward by sending a sinusoidal wave in the appropriate direction along the fin; and I will have a lot more to say about his locomotion in next month's talk. But obviously the fin achieves nothing except when the fish is surrounded by its watery medium. Likewise for land animals, hands and feet achieve nothing in the way of locomotion except in reaction to a resisting medium or surface. Bearing that in mind, I hope you will not think it too fanciful of me to suggest that, from a locomotory point of view, the *medium* ought to be counted as *part of the body*. Faraday, I hasten to say, makes no such interpretation of the mechanics of animal locomotion. But electrically, at least, his researches with Gymnotus will contribute to a new image of body, extended continuously throughout the medium and contiguous with all other bodies through its own activity. The Body Electric will possess a distinctive shape and will call for new principles of anatomy.

II
The Experiments of 1838

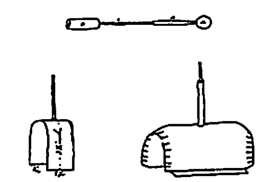
Faraday's experimental exercises with Gymnotus fall into two classes. The first of these may be called "identity" experiments. In them, Faraday confirms through his own work the conclusion he had reached in 1833 when surveying the investigations of others: the animal's electricity is identical to all other electricities in its panoply of effects—physiological, magnetic, thermal, chemical, and so on. Some of his methods are new, but the experimental aims of the identity exercises in 1838 are unchanged from those he had reviewed five years before.

The second exercises are wholly new. Faraday characterizes them as "experiments relating to the quantity and disposition of the electricity in and about this wonderful animal" [1769]; I will call them simply the "disposition" experiments.

The two classes of experiment are different not only in their objectives but in the rhetoric they bring to the animal's electric powers. We can see something of the rhetorical difference between the identity and the disposition exercises by examining their respective apparatus. Faraday describes three kinds of what he calls "collectors," with which to sample the fish's electric action:

First, *the hands*. Here the experimenters subject themselves to shock through their unprotected hands, dipping them in the water while at the same time inciting the fish to discharge. Employing their own bodies as experimental apparatus, the investigators stand in the most intimate possible relation to the object of their study.

Second, *the "disk"* collectors. [SLIDE 9] Here the investigators make their hands only the *indirect* recipients of the shock by grasping the handles of a pair of disk-shaped copper conductors and disposing the disk end variously about the fish's watery element and on his body. These give increased precision of placement, but to some extent their interposition mediates between the investigator and the shock received [1760].



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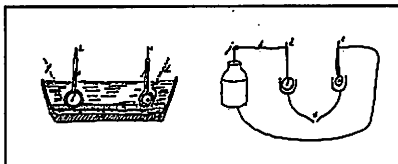
Third, *the "saddle" collectors.* Here the hands are replaced altogether by a pair of copper straps, which Faraday sometimes insulates with rubber jackets. Instead of being hand-held, the saddle collectors sit astride the fish and are wired directly to other indicating devices [1751–1766]; and thus the investigator is placed at still greater removal from the direct electrical effect.

In this short catalog we find an order of increasing sophistication of apparatus—from bare hands to specialized clamps—together with a corresponding regression of the observer from the locus of action. Most of the identity experiments make use of the saddle collectors; thus the investigator in the identity experiments makes only minimal ingression to the scene of action. He does not generally place himself in direct relation with the fish's power, but rather with apparatus that displays *concomitants* of that power.

The identity experiments propound a rhetoric of *mobility.* In them the power is conveyed away from the fish and its habitat. It is separable and has a nature of its own that is studied independently of the fish and in comparison to other "electricities," similarly abstracted from their respective sources. Gymnotus' power can be transferred through conductors to other venues, where it proceeds to display the same phenomena of magnetic action, chemical action, shock, spark, and so on, as electricity generally produces.

It is fair, I think, to say that the identity experiments are more concerned with the electricity than with the fish. Insofar as these exercises portray the fish at all, they represent him as just another electrical source; and hence two images straightway emerge in close succession, both of which focus on the *source* aspect of the animal: Gymnotus as Leyden Jar, and, alternatively, Gymnotus as Voltaic Battery. Both these images are explored in a series of experiments that establish the quantity and intensity of the animal's electrical shock.

[SLIDE 10] Faraday's procedure for establishing *quantity* amounts to a sort of practical pun on the Leyden jar image. He substitutes for the fish in water two brass balls bearing insulated wires, which latter can be connected at will to a Leyden battery of well-documented dimensions [1770, 291]. The Leyden battery is then given its maximum charge. When it is subsequently discharged through the brass balls into the water a shock is felt—quote—"much resembling that from the fish." Faraday continues:



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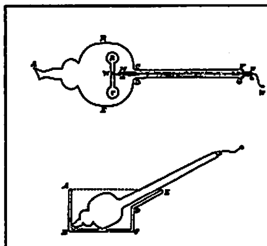
> I think we may conclude that a single medium discharge from the fish is at least equal to the electricity of a Leyden battery of fifteen jars, containing 3500 square inches of glass coated on both sides, charged to its highest degree (291.). [1770]

Judged by the quantities of electricity typically employed in electrostatic experiments, this would be a considerable dose, but one also well within the capabilities of a few moments' action by a large Voltaic battery. Quantitatively, then, both the Leyden jar and the Voltaic battery serve equally well as preliminary images for the fish *qua electrical source.* But even in this restricted role there is no question of taking either image as a literal *explanation.* For one thing, neither image can be easily fitted to the animal's ability to deliver a *series* of shocks in rapid succession [1771]. Basically, the problem is that neither image allows for an "on-off" switch.

Such a failure to articulate the animal's ability to control its action would be fatal to a hypothesis, if that were Faraday's aim. But Faraday is pursuing an *image,* not a hypothesis; and therefore in his subsequent exercises with Gymnotus he will continue to call upon laboratory devices like the Leyden jar as metaphors.

Earlier investigators had sought to solve the mystery of animal electricity by a more literal appeal to some sort of internal battery in the fish. [SLIDE 12] In 1775 Henry Cavendish had constructed a model torpedo-fish out of shoe-leather. He equipped the model with a pair of metal plates which, suitably situated, and energized by a Leyden battery, served as the "electric organs" of his imitation Leviathan. But as his drawings show, Cavendish strove in his model for a measure of verisimilitude in shape as well as material that Faraday evidently regarded as wholly beside the point. Now there is no doubt that to be able to interpret the electric fish as literally containing a source analogous to a Voltaic cell would be of much explanatory value; and it might even seem to advance a more unified view of nature by reducing two apparently different electrical sources to one. But Faraday's conception of the unity of natural forces is more



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sophisticated than any merely reductive program. His view is *relational,* rather than reductive: he will strive to explicate a nature whose unity lies in the inter-convertibility of forces, rather than in anything so literal-minded as expecting to find a Voltaic cell hidden within every electric source. The problem with every image of a *source as such* is that it focuses on the *agent* to the detriment of the *activity;* it tends to represent an "active" source, in isolation from a "passive" object. Images capable of *integrating* the agent and its own power must be sought through a different kind of experiment.

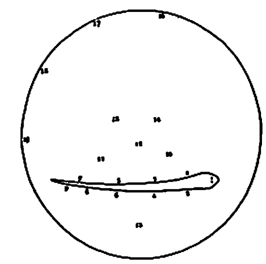
We may therefore turn to the second class of Faraday's Gymnotus exercises. The disposition experiments are carried out almost entirely with either the unaided hands or with the hand-held disk collectors. These are mapping experiments; they employ a rhetoric of *residence.* In contrast to the identity experiments, the fish's power is not here conveyed to a remote observer; rather the observers make full ingression to the scene of action and quite literally immerse themselves in the place of habitation of the power.

A rhetorical contrast between the identity and the disposition exercises is thus evident: the identity of the power is established by removing it *from* its place; the disposition of the power is studied by ascribing it *to* its place. The contrast is not absolute, of course. On the whole, though, the experiments of the Fifteenth Series exhibit two different aims, two different rhetorical dimensions, and eventuate in two different kinds of image—the image of *electrical source,* which we have just discussed, and the image of *system,* to which we now turn.

By the term "system" I think Faraday means to identify not only an inter-dependence of relations, but also an allied condition of *activity:* something like Aristotle's "housebuilder building," which is an agent at work and in an essential relation of *doing* with the surroundings. This is an image which, if it does not actually unify the doer and the deed, at least minimizes their mutual alienation.

Faraday departs in several ways from what had been customary in work with electric fishes. He consistently treats the animal and its surroundings as *essentially* related, not as isolated aspects of the survey. As one sign of this, not one of his experiments calls for removal of the fish from the water [1758]. This is in marked contrast to the traditional torpedo-fish researches, which frequently emphasized the strength and quality of shocks delivered to a handler by a fish held in the air. Certainly Faraday's refusal to do likewise was in part a reflection of concern for the welfare of the animal [1754]; but it may also indicate that his view of the fish—and of agents in general—was already one that strove for unity in the treatment of agent and medium. If so, it would follow that a study of the animal *in its accustomed medium* would better reveal the nature of its characteristic action. While this principle is not exactly the same as that of the animal ethologist, nevertheless we shall find that the fish's habitual behavior is a source of rich guidance to Faraday in the interpretation of its electrical activity.

[SLIDE 13] A survey with the *hands* gives the most comprehensive picture of the state of Gymnotus' body at the time of shock. A single hand placed anywhere on the fish's body feels only a feeble disturbance during a shock, and then only in the part of the hand that is actually in the water [1774]. Two hands placed at the same spot, or even laterally opposite each other, give the same weak result [1773].



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But two hands placed axially along the body of the fish transmit considerable shock, often—in Faraday's words—"extending up the arms, and even to the breast of the experimenter." Within limits, the greater the longitudinal distance between the hands, the greater the shock [1776]. Maximum shock is received when the fish is grasped with one hand just behind the head and the other about six inches from the end of the tail [1760].

Manual survey of the water reveals a similar continuously electrified condition in the surrounding medium. *One* hand placed in the water, or two hands placed together, delivers at most a sensation of tingling—Faraday calls it "the pricking shock" [1781]—and only in the part immersed. But *two* hands placed apart transmit strong shocks up the arms if their line of separation is parallel to the fish, as 10-11 or 14-15; if perpendicular, however, as 12-13, then only weak sensations in the immersed portions of the hands.

When several colleagues take part together, the shock is felt simultaneously at all locations, though with diminishing severity at increasing distances from the center of the fish. Thus at 10-11 the shock is strong, at 14-15 less strong, at 16-17 very feeble, as also at 18-19 [1777–1781]. The occurrence of simultaneous shocks throughout the water shows, what is probably no surprise to us, that discharge occurs throughout *all* the surrounding medium. Amazingly, this was still a live question for Faraday! On 16 October 1838 Faraday had written in his laboratory Diary:

> Now endeavd. to ascertain whether three or four persons, each forming a separate circuit, could be shocked at once and without touching the fish; i.e., whether the discharge is in every direction through all the surrounding water or other conducting matter. (*Diary*, 5017)

If, as is not the case, shock *did* occur in only one part of the medium or along only one path at a time, we should probably be led to seek in the medium some process comparable to a *spark*, for it is characteristic of the spark that it tends to establish only one path at a time between the same points [1407ff.]. What would this amount to but to invoke an image of Gymnotus as *Zeus the Thunderer,* who can throw his fiery bolts to one place, and spare a neighboring place, as he sees fit? But the differentially electrified state of the water, clearly revealed by the concurrence of simultaneous shocks, completely overthrows any thunderbolt image. It is now abundantly clear that Gymnotus does not "throw" a bolt of power to a particular place, independently of neighboring places. Whatever the fish does, it must energize the water *as a whole.*

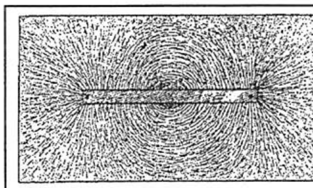
But if Zeus the Thunderer is banished from the scene, another, even more potent image for the fish emerges. Gymnotus is presented as an agent that *occupies space through its peculiar action.* Faraday writes:

> [A]ll the water and all the conducting matter around the fish through which a discharge circuit can in any way be completed, is filled at the moment with circulating electric power. [1784]

The fish is here seen as the bearer of an action that fills space. Or, since Faraday's images generally tend towards the concrete, this one too develops specificity. It will become an image of *Gymnotus as Magnet.*

III
The Fish as Magnet

Results from the manual survey are rough, fragmentary, and highly dependent on the ability of individual investigators to correlate their respective impressions of the animal's shock. Faraday emphasizes that a general pattern becomes evident only after many repetitions of such observations [1782]. But something more than repetition is needed to combine those experimental soundings of the fish's neighborhood into a coherent, readable pattern. Faraday relies heavily upon [SLIDE 14A] the pattern of *magnetic lines of force* surrounding a bar magnet to provide the schema for such an integration. With the aid of this magnetic pattern—the one he will in later years name the "sphondyloid" [3271]—Faraday has no difficulty integrating the coarse survey results into a shape that closely resembles that distinctive figure. He gives a small sketch in the *Diary*. [SLIDE 15]



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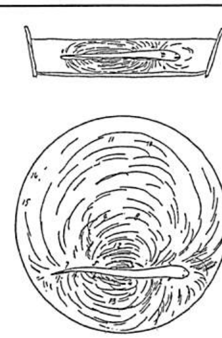

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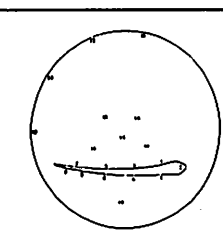
In the *Experimental Researches* Faraday verbally notes this resemblance to the magnet [1784] and virtually invites the reader to make a similar diagram for himself; yet Faraday does not publish any such drawing—neither the sketch from the *Diary* nor any other. I think his reluctance to present this most important image visually in a published paper may arise just because the manual survey *is* so coarse [1782]. Any sketch could only be, as the sketch in the *Diary* is, an "artist's rendition"—a vehicle for the imagination, perhaps, but not a depiction of *facts*. There are in fact no *lines* visible about the fish; Faraday is rather appealing to the magnet, in which the lines *are* made visible (for example through the aid of iron filings), in order to make visual sense of the fish. Gymnotus is represented both in thought and in experimental practice by the metaphorical image of *Fish as Magnet.* Not that Faraday thinks Gymnotus exercises the same kind of force as the magnet does; but it imposes a comparable geometry of action upon its surrounding neighborhood. Faraday takes as an image for the fish, then, not *a picture,* but rather *the magnet itself.*

Though he is a powerful proponent of the imagination, I sense in Faraday a persistent reluctance to picture its contents. Pictures, it almost seems, are for him Sacred to Fact; when imaginative constructs are to be conveyed, Faraday employs his incomparable gift for verbal narrative instead. It is that language that now takes on the burden of presenting a further imaginative integration of additional aspects of the fish. The narrative vehicle Faraday chooses here is a particularly striking one. In one brief but dramatic incident the fish begins to develop interpretive independence from its new-found image "as Magnet." Gymnotus had performed a maneuver which, by Faraday's account, is so transparent and readable, the fish might almost be said to have presented its *own* interpretive image. That occasion is:

The Coiling Incident

We have been considering the electric eel as maintaining a fixed, straight, bodily posture. But as the fish will sometimes *bend* itself from side to side, Faraday describes the effects that such inflections of the body would be expected to have upon the external distribution of the shock. "(T)he lines of force...." he says, "vary in a manner that can be anticipated theoretically" [1783]. [SLIDE 16] First, he explains, a handler who grasped both head and tail of the bent fish would feel a reduced shock, because the shorter water path created by the mutual approach of head and tail permits a greater portion of the force to pass through the water; less, therefore, up the arms. But for that very reason, he continues,



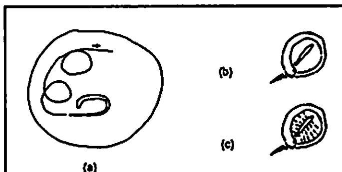
Slide 16

> ...with respect to the parts *immersed,* or to animals, as fish *in the water* between 1 and 7, they would be more powerfully, instead of less powerfully, shocked. [1783—Faraday's italics]

As we soon discover, a bending, or rather *coiling,* maneuver by the fish was not hypothetical but had actually taken place. I hardly know whether the following incident attracts more interest from an electrical, or from an ethological, point of view. Here it is; Faraday is the narrator:

> This Gymnotus can stun and kill fish which are in very various positions to its own body: but on one day when I saw it eat, its action seemed to me peculiar. A live fish about five inches in length, caught not half a minute before, was dropped into the tub. The Gymnotus instantly turned round in such manner as to form a coil inclosing the fish, the latter representing a diameter across it; a shock passed, and there in an instant was the fish struck motionless, as if by lightning, in the midst of the waters, its side floating to the light. The Gymnotus made a turn or two to look for its prey, which having found he bolted, and then went searching about for more. ... The coiling of the Gymnotus round its prey had, in this case, every appearance of being intentional on its part, to increase the force of the shock, and the action is evidently exceedingly well suited for that purpose (1783.), being in full accordance with the well-known laws of the discharge of currents in masses of conducting matter; and though the fish may not always put this artifice in practice, it is very probable he is aware of its advantage, and may resort to it in cases of need. [1785]

For this incident, too, Faraday had made a sketch for himself in the *Diary* [SLIDE 18] that does not appear in the published paper. Here (a) is Faraday's representation of the prowling fish. In (b) is his original sketch of the coiling action. In (c) I have filled in the path of concentration of force, at least as implied by its deadly effect on the prey.



Slide 18

An important stylistic feature of Faraday's account of the coiling incident is his effort to convey what is evidently for him the eminent *readability* of the fish's behavior. The theme of *concentration of the ambient power* is evidenced by the unusually sudden and intense convulsion delivered to the prey—emphatically conveyed in Faraday's phraseology: "in an instant ... struck motionless, as if by lightning...." *Electrical* readability in this episode derives also from the *volitional* readability of the coiling gesture. Since Gymnotus' shock is generally for the sake of killing his prey, a gesture that enhances his habitual hunting behavior implies also an *enhancement of lethal* power—hence a *concentration* of force onto the prey. That the fish must *bend its own body* in order to effect an apparent focusing of its external power suggests, if it does not actually imply, a definite though flexible *structure* in the external action, itself a kind of body or extension of body; a body, moreover, whose substance is not matter but *force*. Once again we have occasion to reject the image of Zeus and his thunderbolt: Gymnotus' shock is not to be viewed as a separable armament, but a functional extension of the body. It is not a weapon wielded, but a limb employed.

The twin anatomical principles of this new body are *contiguity* and *coherence.* In contrast to the specialized organs, ligaments, and conduits of a physiological body, in this new Body Electric action is *everywhere.* It is voluminous and fills space, yet it is not contained either by a membrane or a vessel. It is shaped, but not by a container—rather by its own relations of equilibrium. It is, in 1838, an admittedly enthusiastic and somewhat fantastic metaphor; yet by 1852 Faraday will be speaking essentially the same language—honed, disciplined, and enriched by a series of brilliant magnetic researches—about the lines of magnetic force, that most profound, pervasive, and fertile of all his images.

IV
The Magnet as Fish

The course of development of Faraday's interpretive images is always a dialectical one, laced with tension and reversals. In the case of Gymnotus he began with tentative representations; first as Voltaic cell, then as Bar-magnet. These images were, it seems, necessary first stages in the attempt to visualize Gymnotus' peculiar activity. Yet they were no sooner invoked than revised, and finally surpassed.

The increasing interpretive independence of animal electrical action, gained largely through the interpretive role of such volitional actions as Gymnotus' coiling, comes to a brief but instructive culmination some fourteen years later in which the fish not only frees itself from the magnet metaphor but actually inverts it. In June 1852 Faraday will bring forth his most profound and comprehensive interpretation of magnetic power in the great essay, "On the Physical Character of the Lines of Magnetic Force." There he will argue that the lines of magnetic force are not merely representative symbols but *real structures physically present* in all the materials through which they run, structures present even in so-called empty space. But when Faraday expounds the magnet under this view he uses the electric fish as one of his explanatory images, thereby placing the fish *prior* in explanatory order to the magnet!

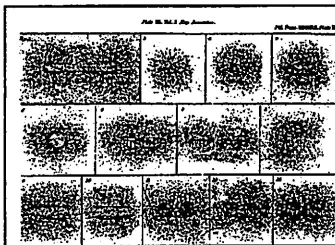
> The magnet, with its surrounding sphondyloid of power, may be considered as analogous in its condition to a Voltaic battery immersed in water or any other electrolyte; or to a gymnotus (1773. 1784.) or torpedo, at the moment when these creatures, at their own will, fill the surrounding fluid with lines of electric force. [3276]

In 1838 the image was *Fish as Magnet:* in 1852 the image is *Magnet* as *Fish.* How did the electric fish, which formerly had been interpreted *by* the magnet, come to be the interpreter *of* the magnet?

As Faraday introduces this reversal of images in the 1852 essay, his immediate topic is the external geometry of the magnet's power. But beyond that, Faraday is concerned to convey his sense that the exterior action of the magnet represents an integrally-shaped, and quantitatively definite, *physical structure.* It is in this service that the electric fish is called to the scene. True, Faraday had revealed the definite *quantity* of magnetic action during the previous year through the phenomena of the Moving Wire [3109]; but it was the early studies of the Voltaic cell, and especially the Gymnotus mapping exercises of 1838, that had given the first intimations of a power that *fills up* its medium, and whose exterior action bears an *essential relation* to the interior condition of the agent.

In order to convey his vision of the *magnetic* lines of force in 1852, Faraday describes typical methods for making visible the lines of *electric* force about an immersed voltaic battery [3276]. *These procedures are virtual recapitulations of the 1838 Gymnotus exercises!* For example, he describes how the lines of electric force may be probed with the galvanometer; for if its leads are dipped into the conducting fluid the instrument will show deflection when the line joining its collector ends is parallel or oblique to the lines of electric force, but no deflection when at right angles to those lines. This exercise rehearses the earlier Gymnotus mapping, both with hands and with the disk collectors [1775–1781].

Another element in the 1852 reversal of images is Faraday's appreciation of *shape* and *proportion* in magnetic systems. Variations in form of the magnet, it is clear, correspond to the coiling configurations of Gymnotus. Faraday will devote five full pages of the 1852 essay to a lovingly detailed exposition of the changes in external disposition of magnetic power that result when a bar magnet is bent, stretched, or squeezed out of its original proportions. [SLIDE 20] All the differently-shaped "atmospheres" of magnetic lines of force shown here are in that essay revealed as derivatives and variants of the standard "sphondyloid" shape.



Slide 20

Recognition of the generic topology of magnets depends heavily on the study and interpretation of magnets fabricated in a variety of shapes, and upon the study of changing conditions in the surrounding medium. From the mutual relations thus revealed between the magnet's shape and the external disposition of its force arises Faraday's magnificent vision of the essential equality and necessary connection between the "inner" and "outer" action of a magnet. He writes:

> The physical lines of force, in passing out of the magnet into space, present a great variety of conditions as to form... [T]he form of the magnet as the source of the lines has much to do with the result; but I think the surrounding medium has an essential and evident influence... [3275]

But the Gymnotus had bent and distorted *itself* in the course of its habitual movements fourteen years earlier, and in its natural predatory activity it presented *itself* in multifarious electrical relations to other animals. *Gymnotus's habitual behavior thus had occasioned the direct display of much the same topology for the animal that artifice and more ingressive experimentation later make evident for the magnet.* The animal's habitual action was also a self-interpretive, heuristic action. In the 1852 essay Faraday reflects:

> When, therefore, a magnet, in place of being a bar, is made into a horseshoe form, we see at once that the lines of force and the sphondyloids are greatly distorted or removed from their former regularity; that a line of maximum force from pole to pole grows up as the horseshoe form is more completely given; that the power gathers in, or accumulates about this line, just because the badly conducting medium, *i.e.* the space or air between the poles, is shortened. A bent voltaic battery in its surrounding medium (3276.), or a gymnotus curved at the moment of its peculiar action (1785.), present exactly the like results. [3282]

The efficacious relation between shape of external action and shape of the body proper can be read more surely in the magnet, thanks to Gymnotus having already called that vision forth for itself fourteen years before.

The 1852 reversal of explanatory order will thus stand as a confirmation, albeit a retrospective one, of some of the intimations of intelligibility and readability in animal powers that Faraday had been responding to in his 1838 Gymnotus report. The promise held out by animal powers cannot claim finality, for the earlier image of Gymnotus falls far short of the later vision of the magnet in comprehensiveness and depth. Nevertheless Gymnotus may be credited with presenting a more accessible starting-point for the ultimate vision than the magnet itself could provide. Its "promise" might best be described, therefore, as *inviting* or even instructional. Gymnotus' contribution to the elucidation of the magnet does not consist of *data,* perhaps not even of *concepts.* It provides rather a concrete object which both invites and serves as the practice-ground for a kind of thinking that will ultimately be demanded by the magnet. The Gymnotus in his tub becomes a *school for interpretation.* Or if not a school in its own right, Gymnotus surely qualifies through its naturally heuristic activities as a constituent tutorial within—to use Faraday's own phrase—"*nature's* school." The brief image reversal in 1852 looks back over a long period of schooling for the image of the magnet.

V
"The very first that I would make"

I said earlier that in 1838 the Electric Eel appeared to Faraday to exhibit the agent-power relation in a way that held promise for solving the riddle of the "on-off" mechanism, the activation and cessation of power. That question is no less than the problem of *will* in animals, and the problem of *force* in agents generally. And though I do not think Faraday can claim very much progress on the question, he does have one thing to say about it, a rather strange and fascinating thing. Whatever it means to *exercise a power,* Faraday will conclude, such exercise must represent a *conversion* of force.

If *to exercise a power* means the conversion or transformation of something actual, rather than the actualization of something potential, then the power so exercised is not specifically the agent's but *nature's:* and the agent is only, as it were, the locus of the conversion. Such Aristotelian language is of course not Faraday's, and at the time of the Gymnotus researches such a view is as yet by no means a paradigm with him. Nevertheless I think that view can help to explain why Faraday finds the volitional activity of animals so promising: the "on-off" cycles of animal electrical action provide an opportunity for studying conversion that inorganic forces, which are always "on," do not permit. Admittedly, that opportunity is in 1838 quite an abstract one; but it is based on a very influential principle. In the realm of nature, at least, we are all inclined to think that *coming-to-be from something* is more knowable than *always-having-been.*

Approaching volitional electrical action as a phenomenon of *conversion* at least points us beyond the "on-off switch" image, which as we saw earlier is just not conformable to animal physiology. Instead of a switch that "blocks the way," like a door or a drawbridge, Faraday will seek a *process* when he looks for an on-off device. And, as ever with Faraday, he conceives this search as a matter for *experiment.* At the very end of the Gymnotus report he proposes a series of experiments whose immediate aim will be to study the conversion relations between—quote—"nervous force" and electric force; but whose overall purpose is to make a further step towards illuminating the agent-power relation.

The electric organs' anatomy, their susceptibility to fatigue, and especially the *constant direction* of the current they produce—all, Faraday says,

> ...induce me to believe, that it is not impossible but that, on passing electricity per force through the organ, a reaction back

> upon the nervous system belonging to it might take place, and that a restoration, to a greater or a smaller degree, of that which the animal expends in the act of exciting a current, might perhaps be effected. [1790]

Faraday has in mind no less an attempt than to *recharge* the fish! He readily admits that such a proposal may seem a very wild idea [1791]. It *is* wild, to be sure; but perhaps not *wildly* wild. As Faraday noted earlier, the electric organs are not vital organs like brain and heart; they are rather like fin and foot. Their office is not essential to the very being of the animal. The experiments Faraday proposes might be delicate and difficult—but in attempting them he would not, at least, be mucking about with *life*. *That* force, it seems, Faraday *does* regard as surpassing our control. He says:

> that exertion [of nervous power] which is conveyed along nerves to the various organs which they excite into action, is not the direct principle of *life;* and therefore I see no natural reason why we should not be allowed in certain cases to *determine* as well as to observe its course. [1791—Faraday's italics]

I note that in the *Diary* Faraday is uncertain whether there may be an opposite current *within* the fish, to correspond with the current *externally* (*Diary,* 4956). In the published report, however, he insists that there must be *some* internal process, equivalent and opposite to the external current [1772]. Faraday's allusion to an opposite internal process seems to have fostered a myth which continues to be propagated by commentators since Maxwell. There is a widespread impression that Faraday's idea is to send a *reverse current* through the electric organ and restore the nervous energy of a fatigued animal the same way we recharge our automobile batteries. But Faraday's words just do not seem to describe a *reverse* current; or they are at least ambiguous enough to make the question of direction debatable.

In the Gymnotus paper there are three passages touching on the direction of Faraday's proposed fish-recharging current; there are none in the *Diary*. I have already cited the first passage, at paragraph 1790:

> ...on passing electricity per force through the organ, a reaction back upon the nervous system belonging to it might take place....

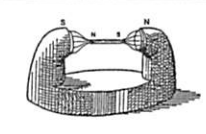
Must "per force" necessarily mean "backwards?" I see no reason to think so. The remaining two passages are at paragraphs 1792–3:

> If a Gymnotus or Torpedo has been fatigued by frequent exertion of the electric organs, would the sending of currents of similar force to those he emits, in the same direction as those he sends forth, restore him his powers and strength more rapidly than if he were left to his natural repose? ... Would sending

> currents through in the contrary direction exhaust the animal rapidly?

I do not see how this wording can be taken otherwise than to suggest that Faraday expects a current in the *usual* direction through the organ ("in the same direction as those he sends forth"), not a *reverse* current, to have a restorative effect on the animal.

If then, as I think, Faraday clearly proposes a *forward* current for rejuvenation, it does not seem that he can be viewing either Gymnotus or the restorative process under the image of a Voltaic battery. Forward current through a Voltaic cell would not only fail to recharge it but would exhaust the cell even more rapidly. But an application of force in the "forward" direction is exactly how we *do* restore a degraded bar-magnet! [SLIDE 25] A weakened magnet can be returned to strength by placing it between the poles of a strong magnet *in its normal direction*—that is, in the direction in which the subject magnet tends to orient itself.



Slide 25

Faraday seems to be following an image of *Fish-as-Magnet,* not that of *Fish-as-Voltaic-cell,* as he contemplates the proposed restorative experiments. And if so, we should ask what reason leads him to favor the one over the other? *Externally,* after all, they are identical; both the magnet and the Voltaic cell imply the same geometry of lines of force in the surrounding medium. And if, as we admitted, it is difficult to conceive how the Voltaic cell could be "turned on and off," there is no less of the same difficulty with the magnet.

But as *sources of power* the two images exhibit a radical difference. The Voltaic cell must eventually become exhausted and fail. Even a rechargeable *secondary* cell acts by gradually consuming a fixed quantity of chemical action. Is that not the lesson of Faraday's celebrated law of electro-chemical proportion? The chemical battery is *mortal.* A magnet, by contrast, does not languish in any comparable sense. Magnets can be damaged or destroyed—as Aristotle would say, through *βία,* violence. But how different this is from the Voltaic cell whose *activity* and *mortality* are realized together. In the magnet we find no reservoir to be exhausted, no life's course to be run.

Might Faraday have seen in the *magnet* a disposition of power more nearly approaching to an image of *life?* Might the proposed direction-protocol in the restoration experiments reflect a suspicion, or even a conviction, that *living power* cannot be imaged according to a logic of finitude and rationing? If Faraday ever did entertain such leanings, however, there is a good deal of evidence that he also resisted them, especially as a younger man. Nor was the magnet's mode of exerting its power a problem Faraday would ever sufficiently clarify to his own satisfaction; the whole picture of Faraday's view of *living powers* remains far from clear. So I must be content to offer the suggestion as my own "wild idea" in homage to Faraday's earlier one [1791]. Yet there is another indication that disposes me to take it seriously. Faraday's closing words in the Fifteenth Series characterize his proposed restorative experiments this way:

> Such are some of the experiments which the conformation and relation of the electric organs of these fishes suggest, as being rational in their performance, and promising in anticipation. Others may not think of them as I do; but I can only say for myself, that were the means in my power, they are the very first that I would make. [1795]

The very first experiments that he would make—this from one of the most celebrated experimentalists of the day! That is extraordinarily urgent language, it seems to me. The urgency may, for all I know, arise for Faraday from strictly mundane considerations and may not reflect a particularly intense interest in *living powers* at all. Nevertheless, a topic more deserving of Faraday's pressing attention than *mortality in nature,* I cannot imagine.

Howard Fisher