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FROM THEORY TO EXPERIMENT AND BACK AGAIN

In this article I consider two substantive examples of the way in which there is continuing interaction in science between theory and experiment. The picture of theory often presented by philosophers of science is too austere, abstract and self-contained. In particular, the picture of theory that is painted is much too removed from the shock effects of new experiments. Perhaps even more to the point, in many parts of science the actual formulation of theory is much driven by the latest experiments.

The first example comes from scientific research I am currently doing on language and the brain. I begin by describing the work in broad terms. I then present the response of new experiments and new theoretical statistical analysis of the data to answer claims that the recognition rates for brain-wave representation of words and sentences is not significant, because of the large amount of information available. Here the use of the concept of an extreme statistic is used to answer this criticism in a detailed way. Discussion of this example will end with some brief remarks on how this use of more detailed statistical methods is now generating new experiments, and having an impact on the design of the experiments.

The second example deals with experiments and physical theory on the entanglement of particles, and the consequent nonlocality of standard quantum mechanics. After some general remarks on this area of research in quantum mechanics and its philosophical importance for our basic physical concepts, I turn to the theoretical work of Greenberg, Horne and Zeilinger and their proposed "GHZ-type" experiments.

First the purely theoretical result, formulated in probability-one terms, is stated. Then the question is asked, how can such probability-one theoretical results be tested, given the inevitable inefficiences of particle detectors.

This prompts a new theoretical effort to derive inequalities, like those of Bell for other experiments, to deal with GHZ-type experiments. What comes out of the analysis is that better experimental results should be achievable with very careful design and use of current photon detectors. But the proof

M.C. Galavotti (ed.), Observation and Experiment in the Natural and Social Sciences, 1–41.

of this is rather detailed and relies on theory in critical ways at several points. These examples are but current illustrations, but the lesson is meant to be universal. The continual interaction between theory and experiment occurs in nearly every developed branch of science.

LANGUAGE AND THE BRAIN[1]

Some historical background

Aristotle said that the distinguishing feature of man as an animal is that he is a rational animal, but, in more biological and psychological terms, it is that of being a talking animal. Language is, in ways that we have not yet fully explored, the most distinguishing mark of man as an animal. Its processing is centered, above all, in the brain, not just for the production of speech, but for the intentional formation of what is to be said or for the comprehension of what has been heard or read. So it is the brain's processing of language that is the focus of this section. I begin with a historical sketch of the discovery of electrical activity in the brain.

An early reference to electricity being generated by muscles or nerves of animals comes from a study by Francesco Redi (1671), who describes in this way an experiment he conducted in 1666: "It appeared to me as if the painful action of the *torpedine* (electric ray) was located in these two sickle-shaped bodies, or muscles, more than in any other part." Redi's work was done in Florence under the Medici's. These electrical observations were fragmentary and undeveloped. But the idea of electrical activity in the muscles or nerves of various animals became current throughout the eighteenth century (Whittaker 1951, Galvani 1791). Yet it was more than 100 years after Redi before the decisive step was taken in Bologna by Luigi Galvani. He describes his first steps in the following manner:

> The course of the work has progressed in the following way. I dissected a frog and prepared it... Having in mind other things, I placed the frog on the same table as an electric machine. When one of my assistants by chance lightly applied the point of a scalpel to the inner crural nerves of the frog, suddenly all the muscles of the limbs were seen so to contract that they appeared to have fallen into violent tonic convulsions. Another assistant who was present when we were performing electrical experiments thought he observed that this phenomenon occurred when a spark was discharged from the conductor of the electrical machine. Marvelling at this, he immediately brought the unusual phenomenon to my attention when I was completely engrossed and contemplating other things. Hereupon I became extremely enthusiastic and eager to repeat the experiment so as to clarify the obscure phenomenon and make it known. I myself, therefore, applied the point of the scalpel first to one then to the other crural

[1]This section is taken from my forthcoming book *Representation and Invariance in Scientific Structures,* Stanford, CA: CSLI Publications.

nerve, while at the same time some one of the assistants produced a spark; the phenomenon repeated itself in precisely the same manner as before.

(Galvani 1791/1953, pp. 45–46)

Galvani's work of 1791 was vigorously criticized by the well-known Italian physicist Alessandro Volta (1745–1827), who was born in Como and was a professor of physics at the University of Pavia. Here are his words of criticism, excerpted from a letter by Volta to Tiberius Cavallo, read at the Royal Society of London:

> The name of animal electricity is by no means proper, in the sense intended by Galvani, and by others; namely, that the electric fluid becomes unbalanced in the animal organs, and by their own proper force, by some particular action of the vital powers. No, this is a mere artificial electricity, induced by an external cause, that is, excited originally in a manner hitherto unknown, by the connexion of metals with any kind of wet substance. And the animal organs, the nerves and the muscles, are merely passive, though easily thrown into action whenever, by being in the circuit of the electric current, produced in the manner already mentioned, they are attacked and stimulated by it, particularly the nerves.
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> (Volta 1793/1918, pp. 203–208)

Galvani was able to meet these criticisms directly and in 1794 published anonymously a response containing the detailed account of an experiment on muscular contraction without the use of metals (Galvani 1794). The original and important nature of Galvani's work came to be recognized throughout Europe. The prominent German physicist Emil Du Bois-Reymond (1848) summarized in the following way Galvani's contribution:

1. Animals have an electricity peculiar to themselves, which is called Animal Electricity.
2. The organs to which this animal electricity has the greatest affinity, and in which it is distributed, are the nerves, and the most important organ of its secretion is the brain.
3. The inner substance of the nerve is specialized for conducting electricity, while the outer oily layer prevents its dispersal, and permits its accumulation.
4. The receivers of the animal electricity are the muscles, and they are like a Leyden jar, negative on the outside and positive on the inside.
5. The mechanism of motion consists in the discharge of the muscular fluid from the inside of the muscle via the nerve to the outside, and this discharge of the muscular Leyden jar furnishes an electrical stimulus to the irritable muscle fibres, which therefore contract.

(Du Bois-Reymond 1848/1936, p. 159)

A next event of importance was the demonstration by Carlo Matteucci (1844) that electrical currents originate in muscle tissue. It was, however,

http://www.springer.com/978-1-4020-1251-8

Observation and Experiment in the Natural and Social Sciences
Galavotti, M.C. (Ed.)
2003, X, 357 p. 8 illus., Hardcover
ISBN: 978-1-4020-1251-8