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The Metaphoric Sources of Scientific Innovation*

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1. Introduction

Metaphors and Analogies occupy a prominent place in our scientific discourses as well as throughout all human communication. In literary studies, linguistics, and the social sciences metaphor is often understood as a communicative trope—the application of a descriptive term to something to which it does not literally apply. That traditional characterization of metaphor assumes that language is a symbol (or code) system which is processed in the head of each individual, and that metaphor is a kind of processing of symbols. From that perspective metaphor is a purely linguistic phenomenon. Since the mid-twentieth century this traditional idea has been questioned and nowadays there are several important lines of research pointing to the importance of metaphor as more than an ornament of speech. The idea that metaphor is a fundamental aspect of human thought was forcefully argued in Lakoff and Johnson's *Metaphors We Live By*. For them, concepts and human language are ultimately metaphorical. That book and the extensive and growing literature elaborating related views has deep philosophical significance. To what extent are metaphors constitutive of thought and exactly what is meant by this assertion? If metaphors are constitutive of thought, are we not obliged to defend some sort of "cognitive relativism" which invites us to think that reality is ours to rewrite? One can formulate the discussion as leading to a choice between two exclusive alternatives: either metaphors tell us what reality is (and thus depending on the metaphors we use reality is different) or else metaphors ultimately are just tools that when used appropriately help us to track reality, and when used inappropriately mislead us. This dichotomy must be rejected, however. Metaphors help us to understand reality by guiding us to construct the right concepts for the task at hand. It follows that the distinction between the role of metaphors in communicating knowledge and their explanatory role cannot be sharply distinguished.

In the next section we show that the role of metaphors in communication involves their participation in shaping the meaning of what is communicated. In section 3 we will make clear why metaphor should be understood as something more than a figure of language. Taking lesson

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from anthropologists and psychologists, we will use the term *material* metaphor to emphasize the importance of the embodied, material dimension of metaphors. In section 4 we will present a series of cases from the history of science that illustrate different ways in which metaphor plays a role in processes of scientific innovation. These are divided in three parts. First, we examine the role of metaphors in making relativity theory acceptable to a wider community, thereby supporting the assimilation of the scientific change that this radical theory implied. In section 4.2 we will examine how Darwin used a series of related metaphors to develop his theory of evolution, and in section 4.3 how scientists in the late 18^{th} century used different metaphors to develop explanatory models for nerve excitation.

2. Metaphors communicate and constitute what is being communicated.

Psychologists, linguists and communication scientists have shown that metaphors play a leading role in how we conceive of the topics expressed by it, often implicitly. Even if we are not aware of it, mentioning a metaphor in relation to an event often leads us to certain beliefs or predisposes us to act in ways promoted by the metaphor. Major events like the COVID-19 pandemic have generated a lot of discussions about the sort of metaphors that should be used to communicate the state of the situation to the general public. Initially (and still often in many places) the pandemic has been often described using metaphors related to war. The President of the United States of America, Donald Trump, incessantly used the metaphor of war in his evaluation of the health crisis. Paying attention to the role of metaphors in the communication about COVID-19 became the topic of #ReframeCovid, an international initiative searching for alternative metaphors to the predominant war metaphors. This effort is quite important because it is well known that the metaphors we use lead to associations and beliefs that might be misleading or undesirable. By personifying the virus as a foreign enemy, war metaphors tend to reinforce xenophobia and racism and also tend to justify authoritarian measures associated with countries in war. Elena Semino, a linguist expert on metaphors, suggests that media should promote instead the use of metaphors like "forest fire", and metaphors related with prevention, thus discouraging our readiness to think in terms of conflict (between countries in particular) and promoting a more cooperative attitude (2021). Notice that such concepts associated to the metaphor "go together" and support each other (see Carrillo 2018). A forest fire requires cooperation, a vigilant attitude to prevent further fires, and firefighters—not soldiers and weapons. Prevention and precautionary measures are key resources for dealing with a forest fire.

Critical events like a pandemic have consequences for the way we perceive ourselves in the world and lead to the reorganization of social life, often in rather unexpected ways. It is not feasible to separate the issue of communication from the question about the role of metaphors in constituting the world (via their role in explanation), unless we make very strong metaphysical assumptions about the reality that matters. But the nature of this reality is not something we can assume beforehand; it has to be the result of scientific empirical research. When communicologists talk about the problem of how best to communicate about COVID-19 it is not assumed that there is something which is *really* COVID-19, independently of how we shape it as a social reality (which can be very different across different communities).

3. Science is Culture and Culture is Material Metaphor

In anthropology and archaeology metaphors increasingly play a major role in explaining the way in which the cultural representation of social experience takes place. In several traditions of anthropology, metaphors are taken to be central to the development of social strategies responsible for the stability and change of individual and group identities. Metaphors lead to major shifts in social organization, particularly through metaphors embodied in rituals and social practices. When metaphors play this role they are often referred to as *material metaphors*. The term is usually associated with a view of cognition as extended or situated, that is, as taking place not only in the head. One of the most basic (material) metaphors is that of the body as a container (Lakoff and Johnson 1980, Gamble 2012). The container metaphor plays a key role in the development of musical instruments and technologies, from ceramic pots to computers. As we shall see in section 4.3 the container metaphor also played an important role in the development of the theory of electricity and neurophysiology.

There are different ways in which the concept of material metaphor has been understood. For us it is enough to say that a material metaphor is a metaphor the basis of which is material culture. Material culture is culture understood as the patterns of interaction constituting the structure of social life and thus our interactions with other people, institutions and artifacts (and technology of course). This is a very rough characterization of material culture, but it is sufficient for our purposes. The main point is that material culture involves our doings in the world understood as collective resources for organizing and maintaining social life (for example in habits, practices and institutions).

As situated (embodied, enacted and extended) cognition theories have been developed in recent cognitive science, and in particular in enactivist approaches to cognition, the concept of material metaphor has gained importance. Such views of cognition are leading to major changes in the social sciences and anthropology (see for example Coward and Gamble's 2010 *Metaphor and Materiality in early prehistory*). The attention to the grounding of metaphor in our skillful interaction with our surroundings has become a powerful tool for models of human evolution and explanations of cultural development. Concretely, it allows the incorporation of (patterns of) behavior in the sort of things that can be brought to play an explanatory role even when we have no direct evidence of such behavior.

The key idea behind the concept of material metaphor has also been developed in several areas of psychology. For example, the metaphoric role of gestures is by now widely recognized as playing an important role in human communication. Gestures can be understood as "material carriers of thinking" (McNeill 2000), and it is also quite clear by now that at least many gestures are metaphors. Wilhelm Wundt in 1922 called those gestures that transfer concepts from one domain to another "symbolic gestures", and the paradigmatic example of such kind of gesture are gestures that represent temporal concepts. In many (but not all) cultures, the future is ahead, in front of us, and we have well known gestures to indicate such idea. In one of the first experimentally based accounts of the metaphoric role of gestures, McNeill (1992) talks of metaphoric gestures presenting an image of an abstraction (like time). For us, then, gestures (or at least an important kind of gestures) are material metaphors.

Communicative gestures of the sort McNeill calls metaphoric gestures, are constitutive of social interactions. Material metaphors like a ritual or a protocol in a scientific experiment have as material basis not a specific human body, but complex cultural artifacts, including skills and a performance space which constraints and norms the performance. Rituals and material metaphors in general can be seen as social gestures, gestures not situated in particular individual bodies but articulated in networks of patterns of interaction like habits and protocols in scientific laboratories. In the next section we show how metaphors, and material metaphors in particular, play an important role in processes of innovation in science.

4. Metaphor, Innovation and Science

Innovation involves finding an unprecedented way to address a situation that brings about some improvement with respect to the outcome the previous course of action used to have. What constitutes innovation has been a topic of increasing importance in the social sciences, education, and the biological and cognitive sciences since the 1960s. The key idea of traditional approaches is that innovations have to overcome the inertia caused by old ways of doing things, which leads specific people or communities to reject an innovation that from a "rational" or "purely economic" perspective should be accepted at once. In other words, innovation, in the form of concepts, technologies, or ways of organization, is often seen as something that happens or is generated somehow in society; and studies of innovation principally aim to explain the factors that impede their acceptance. But this approach to the study of innovation leaves aside the problem of the source of innovation. This problem cannot be separated from the problem of how innovations overcome old ways of doing things and ends up improving ways of doing things (in relation to a given end). Our answer is that metaphors play a key role in accounting for the source of innovation, and the acceptance of an innovation is closely related with the acceptance of the related metaphors.

From the traditional perspective of science as theory-centered it is common to think of metaphors as mere embellishment, or as crutches for understanding to be left at the door once we are capable of understanding the "real" thing (which most often means arriving at a mathematical formulation of a theory). There are important exceptions. Mary Hesse famously argued that all meaning is metaphorical, and this thesis was part of her "network theory of meaning." Her main idea is related with what we have pointed out above, that metaphors play a role in the construction of meaning most often through the mutual support of different metaphors. However, her thesis was still too concerned with the problem of meaning of theories. Here we provide a version of a network theory of meaning that incorporates in a central place the role of material metaphors, and thus the importance of the metaphoric force of artifacts (and instruments in particular).

As the example of the role of metaphors in COVID-19 suggests, and the scientific cases we present in the following cases make clear, metaphors are not mere embellishment. They often play a major role promoting or hindering the development of innovations in science, as they play a key role in passing – from generation to generation of scientists – the knowledge, normative frameworks and skills distinctive of a given practice.

As mentioned in the introduction, using particular metaphors can change the way we frame our problems, and the kind of solutions we propose. Innovation in science is usually associated with words like "revolution" and thus the expectation of discontinuities becomes associated with processes of innovation. But we can think, for example, of innovation in science as mainly a process of "growth" and then of course the connotations are quite different. If we think of science as a process of growth, there is an implicit suggestion that innovations are part of a continuous and "organic" kind of change. The "revolution" and "growth" metaphors can be beneficial or misleading, and each can apply to different kinds of change and can be useful in different contexts to communicate the way innovations take place in different areas of science in different times. We have already mentioned that there is a lot of empirical research in experimental psychology showing the importance of metaphors in shaping our beliefs and guiding us to act in certain ways. Such metaphors play a foundational role in innovation. They exploit what we already know from different contexts, and this leads often to changes of meaning or behavior that can end up being considered innovations. If metaphors have a major cognitive role in the organization and growth of our concepts in everyday life, this should also be the case in science. The question is how this takes place and what is its relevance for the distinctive kind of understanding which science affords.

Next we present different ways in which metaphors shape scientific concepts and play a role in the development of scientific practices and traditions of research. Recall that metaphors are not mere happenings inside the mind of an individual, but have to be understood as a collectively and materially driven phenomenon occurring within social practices. Most often, metaphors play a role in the construction of concepts by joining forces and getting entangled in webs of belief, habits and skills. In science this mutually supporting role of metaphors, habits and beliefs plays a very important role in the generation of innovations. The reason is that the different, mutually supporting (material) metaphors extend our skills and allows us to apply them for the development of novel experiments, theories and models, thus generating new knowledge or skills. When this is the case, it is important consider the material basis of the metaphor to understand its meaning. As we will see in section 4.3, material metaphors are particularly important in experimental sciences. Let us insist here that there is no clear distinction between plain metaphor and material metaphor. The term material metaphor is being used to emphasize this situated, collective and developmental understanding of metaphor grounded in the material culture of science. The next three subsections aim to illustrate the way that metaphors enable innovation in science in different ways.

4.1 Metaphor and Scientific Change

We might be willing to recognize the impact of metaphors in cultural changes in general, but reject the influence of metaphors in the advancement of science. After all, traditional views of science maintain the idea that science is culture, but a different kind of culture altogether: science advances, not only changes. But the idea that science is a fundamentally different kind of cultural enterprise has been challenged by decades of work in the history and sociology of science, and is nowadays also challenged by advances in the cognitive sciences. Thomas Kuhn famously questioned this traditional view of science. His 1962 book starts by claiming that a change in our way of viewing the history of science is necessary to have a better appreciation of what is science: "History, if viewed as a repository for more than anecdote or chronology, could produce a decisive transformation in the image of science by which we are now possessed." For Kuhn science is culture, and as for any culture, history is crucial for understanding it. Contemporary history of science and other social studies of science have gone way beyond Kuhn in studying science as culture. The cognitive sciences have also contributed a lot to this task since they provide ways of understanding cognition as a cultural achievement (above and beyond the achievement of particular individuals). The role of metaphors in conceptual development is an important part of this trend.

Einstein's famous 1905 papers are often mentioned as the beginning of a new era in science, not only in physics. Hermann Minkowski famously formulated Einstein basic idea as follows: "Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality" (Minkowski, 1908). This is a powerful metaphor. Einstein is considered the author of the special theory of relativity because he developed a mathematical framework and a physical interpretation that made it possible to reconceptualize physics, subordinating the categories of space and time to the concept of *spacetime*. The reformulation of Einstein's theory in terms of Minkowski's metaphor led to a general acceptance of the theory and provided a very clear contrast with the former Newtonian physics. The change is momentous. The history of physics up to this point had been developed under the idea that time and space were ontologically two different kinds of entities. Kant had famously given shape to this deep "intuition" supporting the classical framework in a sophisticated philosophical theory. The idea that space and time were mere shadows sounded so counterintuitive to the ears of classical physicists and philosophers that even if willing to accept Einstein's theory as basically right, they tended to reject Minkowski's "metaphorical" formulation of the idea. But in the end this metaphor grew into one of the major reconceptualizations of physics; it plays a crucial role in the theory of general relativity and has had a broad cultural impact.

In academic circles, Einstein's theory also led to the development of concepts like Bahktin's *chronotope*, which elaborates the complementarity of space and time in literary analysis. Major literary works took inspiration from a metaphorical understanding of Einstein's theory. E. E. Cummins invented the term "wherewhen," and the parody of the scientific method in the Ulysses of James Joyce is famous. The work of Jean-Paul Sartre, Robert Musil, Vladimir Mayakowski and Lawrence Durrel are examples in which in different ways the concept of relativity of Einstein was used as basis for the metaphorical elaboration of concepts of relativity in art and science. The change between classical art and modern art was often compared to the break between the Newtonian and the Einstenian views of the world. The idea that Einstein's revolutionary change in worldview should lead to major changes in philosophy and the humanities was echoed in literature and cultural analysis by major philosophers like Bertrand Russell and Ortega y Gasset. The idea that Einstein's theory could be and should be extended to our understanding of morality and aesthetics was also widely shared.

Another major breakthrough in science whose acceptance was forged with metaphors is that of the theory of evolution. When Darwin published his book *On the Origin of Species* in 1859 a major discussion ensued. Most philosophers and scientists that were contemporary of Darwin did not see any major innovation in Darwin's thinking. Herbert Spencer was a highly respected natural philosopher in the second half of the nineteenth century, who had written several books on a theory of evolution. Spencer thought (as many contemporaries did), that Darwin's theory was simply a series of well-documented empirical cases confirming his own views about evolution. Darwin was well aware of this possible misunderstanding and it is well documented that he carefully crafted paragraphs in order to avoid that his theory of evolution by natural selection were confused with Spencer's (and that of other writers of the time). Darwin was so keen in avoiding the confusion that he avoided the use of the term "evolution" in his book. Spencer thought that all change in nature is a consequence of what he called "the survival of the fittest" a phrase supporting a powerful metaphor introduced by Thomas Malthus. This metaphor was widely accepted as a fundamental truth propelling the "evolution" of biological species, which also served as an explanation for many prejudices, for instance that some human "races" were more advanced than others. Ultimately, for Spencer and most of his contemporaries, this was a fundamental law behind all natural changes, a law that lead to the increase of complexity. All cultural achievements, as well as all natural processes were subject to this law. Spencer for example, spent a whole book explaining how the historical development of western music could be explained as a consequence of this universal law.

Darwin was careful to avoid that his theory be confused with such views of evolution, but for decades the confusion was rampant. Beliefs and metaphors supporting a teleological understanding of human history (and all kind of history, including the history of life) were so prevalent that Darwin's innovation was not readily understood. Nonetheless, it has to be recognized that metaphors like the one of the architect can be misleading. Such metaphor can be taken to suggest the role of supernatural intelligence in accounting for evolution, after all, the reference to God as an architect was also common. Metaphors in general are ambiguous and precisely because it is the mutual support of several different metaphors that is often important to arrive to the intended meaning of an innovative theory, as we see below.

4.2 Metaphors Supporting Theories

Darwin’s major concept of natural selection is initially a metaphor which is explained in combination with several other metaphors. Among such metaphors is the tree of life, which describes the diversity of life and the way such diversity has taken place through the history of life, as a consequence of natural selection – another metaphor. These metaphors join forces with many other metaphors. In Darwin’s work, for example, the famous metaphor of the wedge fits nicely to suggest the way natural selection explains the diversity of life: “The face of Nature may be compared to a yielding surface, with ten thousand sharp wedges packed close together and driven inwards by incessant blows, sometimes one wedge being struck, and then another with greater force” (Darwin 1859).

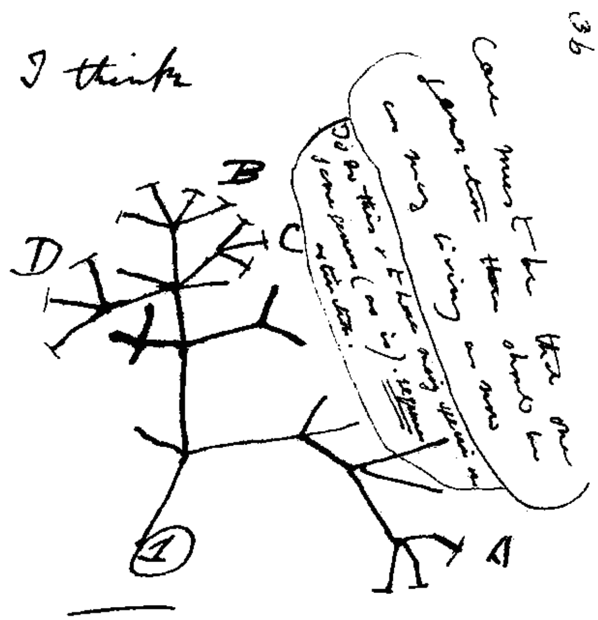

Figure 1. Charles Darwin's first diagram of an evolutionary tree,
from his First Notebook on Transmutation of Species (1837).
Source: Wikimedia Commons.

Notice that the different metaphors are not repetitions, each of them emphasizes different aspects of the process he is characterizing, namely the process of evolution (by natural selection). The reference to a wedge and the geological context brings the attention to a very important aspect of Darwin’s theory, the need to recognize the consequences of a relatively insignificant force through long periods of time (the kind of forces Lyell and other biogeographers of a few decades earlier had recognized and identified as causes of major geological changes in the planet). Whereas Spencer used the metaphor of the struggle for existence to describe the consequences of a fundamental organizing principle of nature characterized a priori, a principle guiding all changes in natural processes, Darwin’s kit of metaphors undermines Spencer’s idea that certain traits will spread and stabilize *as if* some intelligence had selected them. In other words, Darwin is using the metaphor to explain away the sort of metaphysical assumption supporting contemporary theories like Spencer's. In particular, the wedge metaphor makes the point (to a cultivated reader aware of the recent theories about the evolution of the surface of the planet) that there is no need of such intelligence. Small insignificant forces through long periods of time can have major effects. Darwin could expect his readers to be familiar with analogous arguments about the importance of small forces acting through long periods of time as an explanatory resource in Geology. This was a famous and well known theory by the time Darwin published his book.

Another supporting metaphor entering Darwin's argument for the key role of natural selection in evolution is the architect metaphor: "Fragments of rock fallen from a lofty precipice assume an infinitude of shapes—these shapes being due to the nature of the rock, the law of gravity &c—by merely selecting the well-shaped stones & rejecting the ill-shaped an architect... could make many & various noble buildings" (letter 1863). The raw material of natural selection, the varieties that result from imperfect processes of reproduction obey no preordained principle. The architect Darwin has in mind is not solving a puzzle, ordering dispersed pieces to bring forth an underlying order – it is a creative architect, managing to get order out of disorder. It is one thing to make a building with especially shaped stones, and it is another thing to manage to construct a beautiful building with pieces that were not made for that purpose. As he puts it in another of his books: "If our architect succeeded in rearing a noble edifice, using the rough wedge-shaped fragments for the arches, the longer stones for the lintels, and so forth, we should admire his skill even in a higher degree than if he had used stones shaped for the purpose" (1968, 249). The metaphor of the architect emphasizes the sense in which Darwin's theory aims to go beyond Spencer's and other contemporary theories of evolution, precisely by denying the need of an underlying fundamental law, or a supernatural being supporting the creative role of natural selection.

Darwin recognized that he could not give a causal account for the source of innovations required for natural selection to work. Wallace formulated the objection very clearly: natural selection could explain the survival of the fittest, but not the *origin* of the innovations characterizing the fittest (see Martinez 2000, 2019). Darwin had no resources to formulate a full causal explanation, but with metaphor and analogy he had already managed to change the terms of the discussion.

4.3 Metaphor, Explanation and Laboratory Culture

Material metaphors are particularly important in experimental science. Perhaps the metaphor that played the most prominent role in driving neurophysiological research in the second half of the 1700's is the Leyden jar. The Leyden jar was invented around 1745. A precursor of modern capacitors, this artifact consists of a glass jar whose lower half is covered in the inside and the outside with thin sheets of metal. This device is capable of becoming electrically charged and holding that charge for future use. As its name suggests, the Leyden jar was metaphorically seen as a container of electricity. It was usually used in combination with the electrostatic generator that has a turning wheel rubbing onto a cloth and so charges a metal with electrostatic electricity. The metal is then put in contact with the jar's metal tip, and in this gesture the electrostatic electricity travels to the internal metal foil of the jar. The glass in between the sheets of metal or "armatures" in the jar acts as an insulator, impeding charges in the external armature attracted by charges in the internal armature to cross over. To discharge the Leyden jar, it is enough to close the circuit between internal and external armature by touching the metal tip and the external armature with a metallic arch. If the experimenter desires to use the charge of the jar to apply it to some object, a conductor can be placed from the metal tip to the object, then from the object to the external armature, and the Leyden jar discharges the electricity onto the object. Once discharged, the Leyden jar has to be recharged before it can be used again.

Figure 2. *Left*: Apparatus used by Galvani - three Leyden jars. Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0).

In the same decade that the Leyden jar was invented, the scientific community became interested in reports of a South African eel that was capable of giving dangerous shocks. Those who had experienced both the electric shock of the Leyden jar and that of electric fish were struck by how similar they felt (Wu 1984). The Leyden jar then began to play an important role in the development of an electrical hypothesis for the shock that competed with Réamour's thesis that the fish's shock is mechanical in nature. The hypothesis of 'animal electricity' was faced with skepticism, and it would take various decades before it would be more extendedly accepted. The rejection of the hypothesis of animal electricity is a rejection of the idea that an animal could be thought as a container of electricity.

In the decade of 1790, Galvani discovered that it is possible to generate a contraction in a frog leg severed from the rest of the body. This discovery is often regarded in the literature as happening by "chance": while one of his assistants was dissecting a frog leg, a spark jumped from the electricity generator to the scalpel and provoked a contraction of the frog leg. However, some historians consider that even though the event may not have been planned, the whole of Galvani's laboratory was prepared to study the effect of artificial electricity in muscular motion, so it is also not surprising that this finding occurred in such context. Accident or not, Galvani spend a lot of effort trying to reproduce and understand what had happened. He found that if the nerve and the muscle of a dissected frog leg are placed in contact with each of the extremes of the metallic arches like the ones with which Leyden jars are discharged, a contraction is often generated. There was no explanation of these behaviors at the time. Why would a frog leg contract with an electric discharge? Why would it contract when the nerve and muscle are abridged with metal?

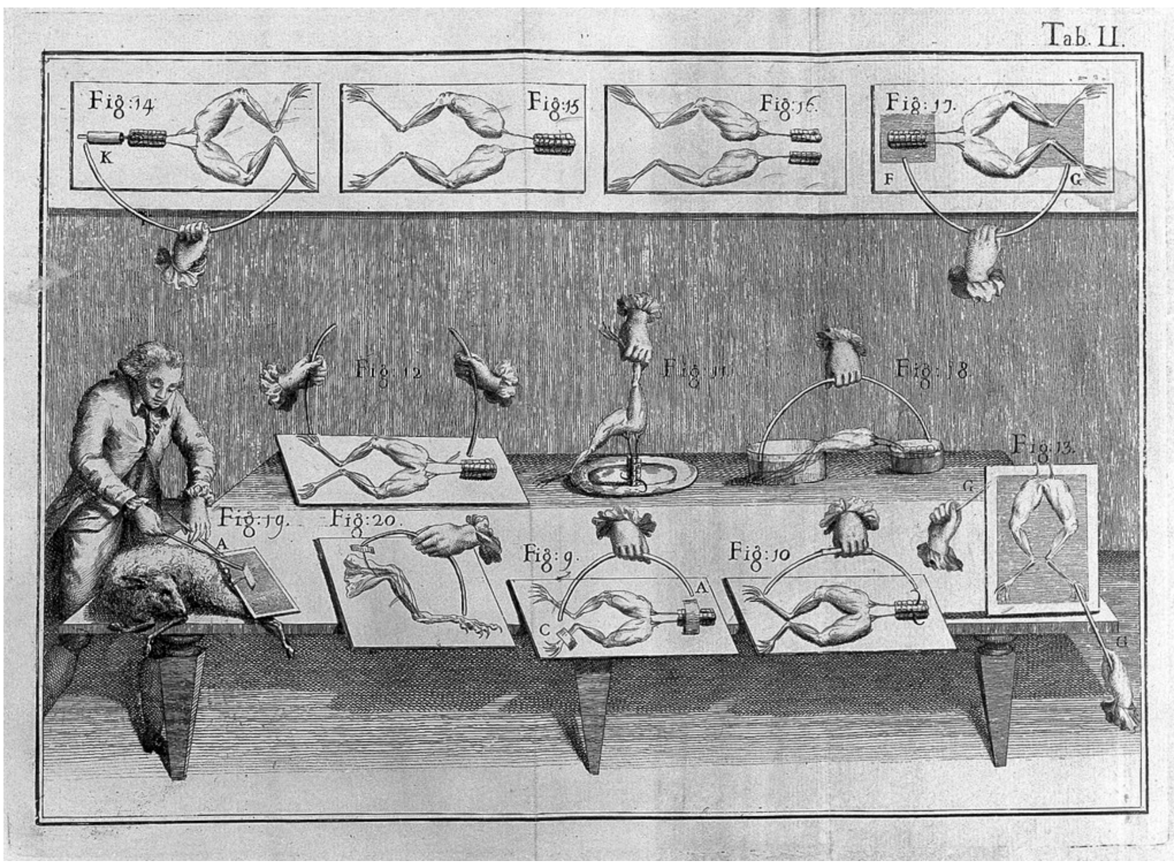

Figure 3. Material culture elements in Galvani's laboratory. De viribus electricitatis in motu musculari commentarius, cum J. Aldini dissertatione et notis. Acc. epistolae ad animalis electricitatis theoriam pertinentes / [Luigi Galvani]. Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0)

Trying to explain the behavior of the frog leg, Galvani resorted to the Leyden jar as a (container) metaphor. Galvani treated the frog leg as a Leyden jar—he not only "discharged" the frog leg with a metallic arch, but also he covered the frog leg with metal foil, which he even referred to as an “armature.” In a first approximation to an explanation of the contraction of the frog’s leg, Galvani proposed that animal electricity is “contained” in the muscle-nerve complex and is “liberated” when short-circuited with the metallic arch, just as it happens in a Leyden jar. However, at this stage the metaphor did not take Galvani exactly where he wanted. The problem was that animal tissue was thought to be an electric conductor at the time, so it was unclear how the electricities could be maintained separate. What was playing the role of the glass in the muscle-nerve complex?

While addressing this issue, Galvani became interested in tourmaline. This mineral becomes electrically charged when heated; and physicists had recognized that this entailed that there is an electrical disequilibrium inside the mineral. In tourmaline the separation of electricities takes place in the micro scale, leading Galvani to a crucial insight: “The double electricity of tourmaline is not just situated in the entire stone, it is in every fragment. Similarly, in muscles, the admitted double electricity does not belong only to the entire muscle body, but to every part of it” (Galvani, 1787, 134; as cited in Piccolino and Bresaola 2013, 134). Galvani elaborated on the first metaphor via tourmaline, leading him to propose a causal (insulating) role for fatty parts of muscle that visually resemble the tiny lines in tourmaline that Galvani believed to operate as insulators. This evolution of the modeling process towards an explanation of the frog leg’s contraction involved the merging of two metaphors: the muscle-nerve complex separates electricities like a Leyden jar, but the insulation operates at the micro scale, as it happens in tourmaline.

As mentioned above, Galvani was not the only scientist to think of organic tissue in terms of a Leyden jar. Rather, the handling and understanding of the Leyden jar was often extended to deal with and explain the behavior of muscles and nerves by scientists of the time. Indeed, electricity was at the time a source of metaphors that promised to solve the great dilemmas of the era, among them the nagging question of whether spirit and body were in some way connected. Scientists of the time also used other electrical devices besides the Leyden jar as material metaphors. For instance, Alessandro Volta argued against Galvani’s hypothesis of animal electricity claiming that the frog leg is not a Leyden jar but an electroscope – it responds to electricity but does not store electricity. In this case, as well as in Galvani’s, it is clear that this was not a purely theoretical issue. Volta actually used the frog leg as an electroscope, since he believed that the electricity came from the metallic arch, and the frog’s leg was much more sensitive to different constitutions in the metallic arches than the electroscopes at the time. Volta would combine different metals and took the intensity of the contraction as a measure of the metallic electricity in the stimulating arch. Weaker contractions indicated the combination of metals used had weaker electric powers. Thus, the frog leg became the electroscope in Volta’s experiments where he examined what he called *metallic electricity.*

In Volta’s and Galvani’s historical dispute, Volta thought that animal electricity does not exist and Galvani claimed that metallic electricity cannot explain the contraction of the frog leg (see Piccolino 1998). The discussion between these two scientists led to two diverging paths of research (see Carrillo and Martínez, forthcoming). For Galvani, the Leyden jar metaphor led to the discovery of a number of behaviors that showed that the frog leg contraction could be held without metals, and proposed an explanation of such behavior. On the other hand, the electroscope metaphor led Volta to a systematic study of how combination of metals generates electricity, leading him to the invention of the pile.

The extended use of material metaphors was not particular of this moment of the history of neurophysiology. Lenoir's nice treatment *Models and Instruments in the Development of Electrophysiology: 1845-1912*, reflects upon the role of instruments in shaping the direction of research: "the instruments used for detection of bioelectric currents in nerves and muscles were significant not just in the trivial sense that they made it possible to explore the key phenomena of the domain, but more importantly, the instruments themselves sometimes suggested, and on occasion even functioned as explanatory models for the phenomena under investigation" (1985, 3). A possible objection to the idea that metaphors are extensively used in science would be to claim that the sort of "metaphoricity" that these scientists engage in may be characteristic of a "premature" science, but that is not how *contemporary* science works. However, as Mary Hesse and several other philosophers of science have already argued (Thomas Kuhn included) this is not a sustainable objection. Moreover, as we have shown elsewhere, throughout the 19th century scientists successfully exploited preparations like galvanic cells and later electric circuits that were extensively used to experiment in squid axons as material metaphors for the nerve cell membrane's behavior, leading even to mathematical models (Carrillo 2018, Carrillo and Knuuttila 2021). More recently still, metaphors coming from thermodynamics have become important in challenging the electrical approaches to study the nerve impulse (Carrillo and Martínez, forthcoming).

5. Conclusion

The idea that metaphor plays a role in scientific innovation is not new. Various authors have proposed that metaphors play a role in the articulation of theories (Kuhn 1962, Hesse 1966, Brown 2003). In this article we focused on the cognitive role of metaphors, material metaphors in particular. The search for the right metaphors to address the crisis generated by COVID-19 is not a search for the right words to talk about the pandemic, it is an effort to grasp the meaning of the pandemic as a social phenomenon which will have major repercussions in the coming years, and simultaneously, the way in which we characterize the pandemic will have consequences. Analogously, Einstein's and Darwin's theories are closely related to metaphors which have had major repercussions in the way the theories have been understood. Furthermore, the metaphors have made connections among broad cultural issues, and thus have helped to situate the theories well beyond the specialized context in which they originated. The metaphors help us situate the novel theories in a broad cultural context, and this process generates meaning. In the case of experimental science, as we have seen with the example of the Leyden jar, the metaphors in question are material metaphors, exploiting the skills and habits associated to laboratory culture to generate understanding. It is such role of metaphor in extending and composing our familiarity with the old to find new ways of acting that enables scientific innovation.

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