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gaston bachelard's philosophy of science: between project and practie

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Without pretending in any way to be laying the foundations of modern physics, I hope to suggest how common philosophical positions must be modified to accommodate reality as it is revealed in the scientific laboratory.
—Gaston Bachelard, *The New Scientific Spirit*

INTRODUCTION

In this paper, I will explore the relation between science as a rational project and scientific research as a human practice. On the one hand, science can be understood as a project manifesting a rationality that transcends the situatedness of human practices. On the other hand, however, science seems to be a fundamental human activity as it is in scientific practices that scientific objects and facts come into being. The French philosopher Gaston Bachelard was among the first to specifically address the relation between the rational and the practical aspects of science, without prioritizing either of the two.

Based on developments in 20th century physics, Bachelard maintains that science is best understood as a collective activity taking place in local scientific practices, and he emphasized that the objects of the sciences exist only insofar they can be realized in what Bachelard calls phenomenotechnique.[1] This concept denotes Bachelard's insights that the objects of physics are not to be found in an external nature, but are artificially realized in scientific experiments and the technologies used in those experiments. When extending to contemporary scientific practices in general, we can no longer understand the different sciences as being concerned with the *discovery* of their objects, but instead with the *construction* of them. Accordingly, the way in which scientific objects are created within scientific practices is the central focus of Bachelard's epistemology.[2]

Nowadays, the idea that scientific objects are constructed in situated practices, and are therefore for a large part dependent on human interventions, figures prominently in (continental) philosophy and anthropology of science. For example, it forms the core of the early work of the French philosopher-anthropologist Bruno Latour, who is interested in studying practices of science-in-the-making, as opposed to focusing on the finished theories and facts of "ready-made science."[3] In showing that the objects of the sciences are actively constructed by groups of scientists, Latour challenges the idea that science is a rational project able to attain universal truths about an external world.[4] In this context, Latour and Woolgar approvingly, yet mistakenly as I hope to show in this paper, refer to Bachelard's concept of phenomenotechnique:

> The artificial reality, which participants describe in terms of an objective entity, has *in fact* been constructed by the use of inscription devices. Such a reality, which Bachelard (1953) terms the "phenomenotechnique," takes on the appearance of a phenomenon by virtue of its construction through material techniques.[5]

In this quote, Latour and Woolgar contrast objectivity with construction. This contrast implies that while the researchers in the laboratory act *as if* they are speaking about an entity that is objectively out there, *in fact* they are speaking about something that is constructed and does not exist outside of the structure of the laboratory. Hence, while Latour stresses that scientific objects are situated constructions realized in scientific practice, he does not explicitly address the question whether there are specific characteristics to their process of production that justify the adjective 'rational,' which was a central question in Bachelard's epistemology. As a consequence, his analyses of scientific practices tend to emphasize the practical character of knowledge production, but often fail to appreciate the rational criterion that warrants the specific practical actions. This brief discussion allows to formulate the question I address in this paper more precisely: How are the 'rational' and the 'practical' integrated in scientific practices? Bachelard was similarly concerned with this question when distinguishing between the practice of the science and the project of science. His work has not received much attention in recent philosophical analyses of scientific practice.[6] In this paper, I propose to use Bachelard's epistemology as an entry-point to the question how 'scientific' and 'practice' are interrelated such that something as 'scientific practice' is constituted.

The paper is structured as follows: Firstly, I show why, according to Bachelard, science can only be realized through an epistemological rupture with our ordinary experience (1). Secondly, I will show how this break is realized in scientific practice by introducing Bachelard's notion 'phenomenotechnique' (2). Thirdly, I discuss why Bachelard holds that a scientific rationality remains to be assumed within phenomenotechnical constructions, and why he holds that scientific objects are not only technical, but also rational realizations (3). Fourthly, I use Bachelard's epistemology to show how the scientific object 'cognition' is realized within the cognitive neurosciences (4). To conclude, I offer some thoughts of how Bachelard's epistemology can be of ongoing relevance by showing how it allows to evaluate the socio-material environment in which science takes place in terms of the interrelation of the practical and the rational within the phenomenotechnique (5).

1. SCIENCE AND THE EPISTEMOLOGICAL RUPTURE

One of the central aspects of Bachelard's philosophy of science is his notion of epistemological rupture, which stresses that there is—and should be—a fundamental divide between scientific experience and ordinary experience. Science should overcome the "obstacles that everyday life has set up."[7] Bachelard juxtaposes the world of everyday life with the world of science, and argues that science should break with our initial experience in order to realize its rational potential. In fact, he holds that science "must be formed against nature, against all that comes from nature's impetus and instruction, within us and outside us, against natural allurements and colourful, diverse facts."[8] Only when successfully suppressing human primary impulses, it becomes possible to enter the domain of science that aims for the development of theoretical knowledge.

According to Bachelard, our initial contact with the world is—contrary to the rationalist purpose of science—grounded in our primary drives that induce reverie and dream.[9] Primitive encounters with objects induce reveries that create images transcending the objects that we encounter. This act of transcending takes place through our primitive drives, and precedes any kind of reflection: "We are being faithful to a primitive human feeling, to an elemental organic reality, a fundamental oneiric temperament."[10] This oneiric aspect of our primary experience is characteristic of the way the reality of everyday life is constituted. Only when overcoming this oneiric state, a rational stance towards the world can come into being. Rationality is a continuous process of overcoming primary impulses: "In point of fact I see no solid basis for a natural, direct, elemental rationality [...] Rationalist? That is what we are trying to *become*."[11]

The second reason for the need for an epistemological rupture between science and everyday life is illustrated in *The Philosophy of No* in the context of developing a scientific understanding of heat: "Between sensory knowledge and scientific knowledge there is a gap. Temperature is seen on a thermometer, one does not feel it. Without theory, one would never know whether what is seen and what one feels correspond to the same phenomenon."[12] We need theory in order to connect the different ways in which temperature can become present to us. Without theory, so Bachelard holds, it is not rationally warranted to infer that the numerical presentation of heat on a thermometer is related to the heat of the sun that we feel on our skin. Only when appreciating the complexity of temperature requires, and breaking with our everyday experiences, it can be understood *that* the concept of heat is complex, and to investigate *how* the different aspects of heat are integrated.

Bachelard explicitly terms his philosophy of knowledge a *non-Cartesian epistemology*.[13] His non-Cartesianism is most clearly visible in his criticism on Descartes's wax argument. In the *Second Meditation*, Descartes argues that wax cannot be clear and distinctly perceived by the senses because its form changes when heated, "for whatever came under the senses of taste, smell, sight, touch or hearing has now changed; and yet the wax remains."[14] This is why he concludes that the idea of wax is not grasped by the senses, but is understood by the mind alone. Bachelard, however, argues that precisely the diverse manifestations of the wax under different circumstances are the basis of scientific research because these complicate our initial experience. When revealing complexity it becomes possible to connect the different complex elements of wax. At the same time, revealing this complexity works against our natural inclination to think of wax as a singular object in our ordinary experience. While Descartes concludes that certainty is founded in a *simplicity* existing in the mind alone, Bachelard holds, on the contrary, that scientific certainty should be found in the *complexity* of the shape of the wax under different experimental circumstances.

In Bachelard's view, when asking for the possibility of scientific certainty, we should not start from the individual mind of the philosopher, but turn to how processes of objectification actually take place within the sciences. When looking at scientific practice, it becomes clear that the scientific objects never exist in the mind alone, but always have a twofold relation with the empirical results of scientific experiments. Firstly, the objects of science are complex objects in the sense that they are connections of different observed phenomena. Secondly, it is in relation with this increasing complexity that science is able to overcome the subjective aspects of ordinary experience, and strive for objectification. Only in this way can we understand the continuous development of the sciences: "subjective [Cartesian] meditation is bent on attaining clear and definitive knowledge; objective meditation differs from this by the very fact that it makes progress, by its intrinsic need always to go further, to extend the limits of the known."[15]

The objective meditation of the laboratory scientist realizes an epistemological rupture with how nature is ordinarily encountered. While Descartes concludes that the changing qualities of the wax force us to dismiss the trustworthiness of sensory experience, Bachelard holds, on the contrary, that it is precisely the experimental revealing of the diverse manifestations of the wax that allows for its objectification. Scientists must continuously be open to experience new objects, which are constituted by how different aspects of them are experimentally revealed. The objective meditation strives to continuously expand the limits of the known through the rational integration of experimental diversity. The extent to which such an objective mediation of the complexity of scientific objects indeed requires, as Bachelard would have it, an absolute rupture with ordinary experience remains up for discussion. However, Bachelard's understanding of the rationality of science in terms of an epistemological rupture opens up the possibility to make clear that scientists in practice construct scientific objects that cannot be reduced to the sensory experiences of scientists. Rather, as is expressed in Bachelard's notion of phenomenotechnique, the realization of scientific objects is one of rationally integrating a diversity of complex phenomena into objects that explain this diversity.

2. PHENOMENOTECHNIQUE

The start of the 20th century was marked by great developments in physics. It saw the birth of relativity theory and quantum mechanics, and broke with earlier theories in physics that were grounded in classical mechanics. According to Bachelard, this break did not just have scientific consequences, but also forced philosophy to "modify its language if it is to reflect the subtlety and movement of contemporary thought."[16] Philosophy should follow the course of these most recent scientific developments, because "science in effect creates philosophy."[17]

One of Bachelard's key epistemological insights is that the objects of 20th century physics cannot be cut loose from the technologies used to observe them. For example, the phenomena observed in the scientific experiments such as electrons, are constructed within scientific experiments, and do not exist independent of the technologies through which they are realized.[18] This is why Bachelard argues that we should understand the objects as constituted within a phenomenotechnique, because "it is then that we understand that science *realizes* its objects without ever just finding them ready-made. Phenomenotechnique *extends* phenomenology. A concept becomes scientific in so far as it becomes a technique, in so far as it is accompanied by a technique that realizes."[19] If epistemology and philosophy of science are indeed to be grounded in the development of science, it should be acknowledged that scientific objects cannot be cut loose from technology, because (i) these are the product of a technical mode of action, and (ii) their existence is instantiated by technologies used in scientific experiments.

According to Bachelard, "when we have followed contemporary physics, we have departed nature to enter in a factory of phenomena."[20] Scientific practices are dependent on the uniform working of scientific technologies, which are interpreted as reified theorems that "provide a certitude which is lacking in more passive knowledge."[21] In this sense, science resembles industrial technology because both depend on the stabilization of their objects. Technologies provide the basis for the construction of scientific phenomena that remain stable in different experimental contexts in a similar way that their use in mass production creates a stability among a set of products. However, we should not conceive of this analogy as a way to diminish the distinction between scientific practices and the practices of mass production in industrial factories. While the maintenance of stability is a sufficient condition for pursuing the ends of technological thinking, this stability must be transcended in scientific practice.

The transcending of the stability of the given phenomenon is what Bachelard describes as the "unanticipated paradox, which shows knowledge to be fleeting and mobile, and the action, which it brings to light to be solid and assured."[22] Although science relies on stable technical actions, attaining knowledge is a matter of moving beyond what is technically created. According to Bachelard, the crucial difference between science and industrial technology must be located in the fact that the end of a technological process for industrial means is part of the way it is realized, while this goal-directedness is absent in science. For example, the working of a water wheel generating electricity can be exhaustively explained in terms of the empirically observable functional mechanism through which a particular amount of electricity is realized. The observation of an electron in a scientific experiment, on the contrary, assumes prior mathematical assumptions that are not part of its realization, but are required to integrate a complex set of observable effects can be integrated into the singular object 'electron.'

Industrial technology deals with closed systems that can be characterized in terms of their finality. The knowledge that is needed of the exact workings of this system is relative to what it intends to achieve: technology aims for an approximate knowledge relative to goals already set.[23] On the contrary, science cannot be limited to the schemes in which technological systems work in everyday situations. Scientific experimenting and theorizing are part of an open process of knowledge development that cannot be described in terms of the ends they serve. Accordingly, the phenomenotechnique that constitutes scientific practice must not be equated with a particular technical mode of action that realizes its goals by employing scientific technologies.

Reminiscent of Descartes, Bachelard distinguishes between *knowledge* and *action*.[24] Industrial technologies are concerned with the domain of everyday life action, while the phenomenotechnique constructs objects about which scientific knowledge can be obtained. The difference between the two becomes clearly visible when contrasting scientific experiments with the technological realization of a certain goal within a closed system. In industrial systems, technological processes are used to continuously make the same product: any unexpected results would be considered failures. In mass industry, the goal is to create a large set of indistinguishable products, and the coming into existence of each individual product can be defined in terms of the actions through which they are created. The objects of science are not the product of a goal-oriented endeavor. Scientific experiments are based on existing hypotheses that structure how an experimental set-up is build, but they are supposed to generate something new by increasing the complexity of the object under study. This is why experiments do more than just testing a hypothesis, because in the confrontation between hypothesis and empirical manifestation, new scientific objects may be realized. In contrast with technology, science is an ongoing open process of hypothesizing and correcting previous knowledge that is contradicted in scientific experiments.

3. THE RATIONALITY OF SCIENCE AND THE PHENOMENOTECHNIQUE

Bachelard interprets the history of epistemology as an ongoing debate between rationalists and realists. He opposes the idea that certain knowledge, i.e. scientific knowledge, must be understood either in realistic terms (knowledge successfully reflects the structure of an external reality) or in rationalistic terms (knowledge is the product of the human mind). According to Bachelard, both of these positions fail to do justice to how science actually works. They are "the results of impermissible abstractions that did not do justice to the complexity of the contemporary sciences."[25] When looking at scientific practice, Bachelard notes that those two positions do not conflict, but "coexist peacefully in the modern scientific mind."[26] Science is as significantly the product of the rational activity of the scientific mind, as it depends on the material manifestation of phenomena in scientific experiments. Accordingly, a philosophy of science should reflect both of these aspects.

According to Bachelard, the new sciences of the early 20th century break with earlier philosophical theories of knowledge in two ways: (i) New science is based on the co-existence of rationalism and realism, and cannot be reduced to either of the two, and (ii) the objects that new sciences speak about are not 'discovered' in 'nature,' but are constructions that are phenomenotechnically realized in scientific practices. Consequently, a philosophy of science should aim to come to a synthesis of rationalism and realism that takes into account the constructed nature of scientific objects. Bachelard uses the terms 'applied rationalism' or 'technical materialism' to refer to the position that adequately reflects this middle position between rationalism and realism.[27] These terms illustrate that a philosophy of science should always oscillate between the rationality of science itself, which creates a domain of inquiry that breaks with ordinary experience, and the constructed nature of scientific objects that are the product of technological manipulations on a rationally plain.[28] No priority should be assigned to either the rationality of mathematics or the way scientific objects become empirically accessible within the phenomenotechnique. The material environment in which scientific phenomena become visible helps realizing scientific objects, but it is only because these can be meaningfully interpreted against an already existing mathematical background that these phenomena become significant. The objects of science appear in an environment that is "mathematically meaningful before it is phenomenally significant."[29]

Bachelard develops his philosophical position by answering the question: 'How are the objects of science made?' Or in Bachelard's words: "Tell me how you are sought and I will tell you what you are."[30] As we saw, in Bachelard's view, science is realized by establishing an epistemological rupture with ordinary experience. Accordingly, the phenomena encountered within the phenomenotechnique should not be related to as objects of ordinary experience. Loosely following the Kantian distinction between phenomenon and noumenon, Bachelard holds that strictly speaking, scientific objects are not grounded in sensory experience, but are the products of mathematical thinking. However, the twist that Bachelard gives to the Kantian distinction conflicts with Kant's conception of the noumenon. While the noumenon is by definition inaccessible in Kant's view, Bachelard holds that the fact that some scientific phenomena can never be perceived does not prevent scientists from having epistemological access to them.[31] Bachelard locates the rationality of scientific practice in the creation of a noumenal plain in which scientific objects appear. Contrary to the Kantian noumenon, Bachelard's noumenon is scientifically constructed and knowable by the human being.

In 20th century microphysics, Bachelard holds, mathematics is a technique through which a noumenon is created in which scientific objects are made accessible. This mathematical grounding distinguishes scientific practices from ordinary practices in which technologies are involved. This does of course not imply that technological systems do not involve mathematical reasoning. For example, the product output of an industrial factory may well be mathematically predicted in terms of the amount of products the machinery is likely to manufacture in a certain amount of time. However, in contrast with scientific practices, the existence of the product (say, a shoe) is not dependent on this mathematical prediction. That is, contrary to scientific phenomena, the presence of mathematics is not constitutive of the existence of technical products.

However, the sciences should not be reduced to their mathematical character. On the one hand, Bachelard argues that the sciences should rationalize reality in order to construct scientific phenomena against nature. On the other hand however, the reality of rationalizations is shaped in the way they become empirically accessible. This empirical realization of rational thought is, according to Bachelard, constitutive of the experimental character of 20th century science. This duality is reflected in the phenomenotechnique of scientific practice: the structure of the phenomenotechnique always works on the basis that a mathematical surface is rationally present, and can only realize scientific phenomena within this surface. This is why, in Bachelard's view, technologies are both reified theorems and provide phenomenal stability across experiments because they perform homogeneous actions. The phenomenotechnique both contains the mathematical technique of creating a noumenal plain, and technologies that allow for the stable appearance of scientific phenomena across experiments.

Science takes place through "the application of the rational technique of scientific thinking [that] determines a genuine recurrence of rationality."[32] This can only be realized through the apodictic acceptance of rational values: it requires what Bachelard calls a *rational apodicticity*. Rational apodicticity makes it possible to break with ordinary experience and engage in a relation with the complexity of the phenomena realized through the phenomenotechnique. Thus, the apodicticity of rationality organizes the experience of scientists and enables them to recognize phenomena not as referring to natural objects but as complex relations out of which the rational objects of science can be constructed. Hence, phenomenotechnique is the recurring rationalization of a rationality that is already established, but must be continuously enacted in order to remain present as a prerequisite for the recurrence of scientific thinking. This is why science is never just mathematical: The objects of science are not merely realized through the rationality of the scientific mind, but are also constituted through their empirical realization within phenomenotechnique.

Bachelard's view that philosophy should be guided by the development of science coincides with his acceptance of these developments as a standard of rationality. As was already hinted at in Bachelard's reply to the Descartes's wax experiment, it is only in comparison with contemporary scientific practices that earlier types of inquiry can appear as irrational, i.e. as not having been able to break with ordinary experience. Bachelard does not refer to any standards of rationality that are external to the actual development of science. Only by looking at contemporary scientific practices can philosophers discover the workings of rationality.

Bachelard holds that science always develops in relation to previous scientific discoveries, and therefore partly involves the incorrect scientific judgments of the past.[33] Furthermore, he holds that scientists can never fully overcome the epistemological obstacles, i.e. they can never fully break with ordinary experience.[34] Science always develops against previous scientific discoveries; it stands always in a dialectical character with its own past. For Bachelard, this means that earlier epistemological obstacles and scientific errors remain a part of present research. It is only in relation with earlier scientific theories and scientific objects that new objects can emerge that can be theorized about, and new standards of rationality can come into being.[35] Accordingly, Bachelard characterizes science as a dynamic process both guided and striving for rationality.

If science requires scientists to engage in a rational apodicticity, the question arises how this apodicticity is realized in scientific practices, and how it subsequently structures how scientific objects come into being. According to Bachelard, it is not the technique of creation that singles out the scientific character of the phenomenotechnique. Whereas the technique of creation brings objects within the field of the human senses, science should "amplify what is revealed beyond appearance"[36], which is for example illustrated in his remarks on temperature discussed earlier. The mere perceptual experience of a (constructed) phenomenon does not warrant its scientific character, but assumes a prior engagement in the rationality of the scientific project.

While Bachelard's epistemology mostly focuses on (micro-)physics and chemistry, he considers all scientific specializations to be rational insofar they participate in the rationalist project of science at large, i.e., they presuppose a rational apodicticity. Yet, when arguing that science has regional rationalisms that belong to the particular sciences, he suggests that the process of constructing scientific objects may differ greatly across the different sciences.[37] However, Bachelard holds that while each scientific practice is different, they are similar to the extent that they are scientific. While they differ in their specific practical make-up, they all are equally concerned with the rationalization of the real. That is, the structure of the particular phenomenotechnique at work within a particular scientific context can only function because it participates in a scientific rationality.

How must we understand the relation between the micro-aspects of practices across the different sciences, and the general rationality of the scientific project? In Bachelard's view, science, as a project, is a manifestation of rationality. Science takes place in a 'scientific city,' and the inhabitants of this city should aim to come to a collective understanding of scientific objects through participating in the rationality of science. In Bachelard's view, rationality emerges out of the social exchanges between scientists. Only within collectives is it possible that individual scientists do not obey their instinctual desires and drives characteristic of an ordinary experience of nature, and are classified by Bachelard as epistemological obstacles that should be overcome.[38]

Also this idea of the scientific city is grounded in how Bachelard conceives of the actual structure of scientific practice. When discussing that most of the papers appearing in scientific journals are written by several authors, he stresses that this cooperative aspect is typical for the way rationality is manifested in *new* science, i.e., in 20th century physics.[39] This collective rationality functions as a model for how science should be organized, and how scientists are capable of communicating among each other in a rational manner. The idea that rationality can only be obtained when participating in actual scientific practice, and by relating to other scientists is most dramatically expressed in Bachelard's latest fragments on poetics that were posthumously edited and published. In the *Fragments of a Poetics of Fire*, he writes:

> I am of the conviction that an active rationalism must be associated with scientific labor, transforming all knowledge into scientific knowledge. Thus, if I were to write a new book as a rationalist, I would have to go to the school of one of the contemporary sciences. One can no longer be *rationalist by oneself*, on the fringe of contemporary scientific activity. It is necessary to learn together with the workers of rationality.[40]

The lonely individual is unable to produce rational knowledge, because rationality is constituted in the scientific city through the discursive practices between scientists. Only in this environment can the human mind engage in a rational apodicticity. The individual, on the contrary, is only capable of producing desires and dreams that are private by definition, and can only be expressed in poetry. Hence, a specific social structure is a necessary precondition for engaging in the scientific project. This collective rationality is not limited to personal interactions between scientists, but also structures how scientists relate to the phenomena they study.

In the scientific city, rationality is expressed in the books that are written about scientific phenomena. This collective discursive layer of the written word provides an extra foundation of the sciences, which adds to the noumenal construction of the scientific plain through mathematical techniques. Polemically, Bachelard refers to this discursive structure as providing a *bibliomenon* that helps providing a stability for the existence of scientific phenomena within the scientific community.[41] Through the constant interaction with the scientific phenomena that exist within the bibliomenon, scientists remain constantly aware that the objects that science is about are not natural objects, but are artificially created. The collectivity of the bibliomenon is especially important for Bachelard, because the irrationality of the our ordinary experience remains constantly present in each scientist.

According to Bachelard, this collective and discursive structure of the scientific city guides how science is practiced on a micro-level. The micro-experience of scientific practice participates in the scientific project that guides scientific thinking. He conceptualizes this scientific project in terms of a rationality that continuously aims to correct previous errors. No matter what technologies, research objects, and concepts are present, the different sciences can all be considered scientific insofar they participate in the rationalist project of science at large. The structure of the particular phenomenotechnique at work within a particular scientific context can only function because it participates in a scientific rationality. Consequently, the micro-activity of scientific practice can only be performed to the extent that they are part of the macro-aspect of science as a rational project.

Scientific objects that are constructed within in a phenomenotechnique can only be appreciated within a structure that supports the possibility of engaging in a rational apodicticity. This structure is realized in the construction of a rational environment in which scientists are capable of continuously overcoming epistemological obstacles in their interactions with each other in the scientific city in which scientific phenomena are stabilized. Only in such an environment can the human mind by rectified such that it overcomes epistemological obstacles. The structure of the scientific city should therefore embody the rationality that is realized within the phenomenotechnique: the rationality present in the way scientific objects are realized in scientific practice should therefore be incorporated in the socio-material environment in which science takes place.

4. PHENOMENOTECHNIQUE AND COGNITIVE NEUROSCIENCE

Let me try to make clear the ongoing relevance of Bachelard's epistemology by discussing a recent development in the cognitive neurosciences, thereby indicating that the notion of phenomenotechnique is not limited to microphysics, but can also be productively extended to other contemporary scientific practices. In the course of the history of the neurosciences, cognitive functions such as 'attention,' 'empathy,' and 'agency,' have been made available for investigation. Researching these specific cognitive functions requires the presence of specific technologies such as *functional Magnetic Resonance Imaging* ((f)MRI) or *Electroencephalography* (EEG), and the active construction of experimental set-ups in which they could be made present. These developments gave rise to specialized discipline of cognitive neuroscience. During experiments in the cognitive neurosciences also participants have an active role because they have to perform certain tasks that are thought to be potential measures of a specific cognitive function. Only within such experiments can brain states be linked to existing conceptualizations of human behavior. In other words, it requires the presence of a phenomenotechnique to realize these cognitive functions *as* scientific objects.

Mathematics plays a formative role within the phenomenotechnique. The brain activity displayed on (f)MRI scans are generated by comparing activity in different regions of the brain, a statistical task heavily dependent on computing power considering that fMRI divides the brain into approximately 138,000 voxels that are compared with one another.[42] Scientists cannot execute such a mathematical analysis independent of a computer, which introduces an opaqueness into the way brain scans are generated. In fact, there is no possibility for neuroscientists to retrace the mathematical processes through which brain scans are generated step by step. Besides linking experimental outcomes to existing psychological concepts to explain human behavior, neuroscientists also have to evaluate how such are concepts are mathematically realized within the phenomenotechnique.

Let me try to make clear with an example how this problem is solved in the neurosciences when considering that scientific objects are the interplay between the phenomenotechnique and a rational apodicticity. In 2012, Craig Bennett and colleagues won the Ig Nobel Prize in neuroscience with a study that showed brain activity in a dead salmon using fMRI.[43] The task that the salmon had to perform is described as follows by Bennett and colleagues:

> The task administered to the salmon involved completing an open-ended mentalizing task. The salmon was shown a series of photographs depicting human individuals in social situations with a specified emotional valence, either socially inclusive or socially exclusive. The salmon was asked to determine which emotion the individual in the photo must have been experiencing.[44]

The point of this experiment is not to detect brain activity in a dead salmon, but to reveal the flaws occurring in statistical analyses in the cognitive neurosciences that did not correct for the so-called *multiple comparisons problem*. This problem states that, when a large amount of statistical comparisons are made, there is a significant chance that the test will yield some random results because of noise fluctuations. These random results are called *false positives*. Bennett et al. aimed to show that without employing statistical techniques correcting for this problem, several areas of the dead salmon's brain were significantly active during the task. This result was visualized in a brain scan that contained red dots representing the brain activity in the significantly active regions: a result that would be an absurdity.

At this point, two things could be inferred: either the dead salmon was indeed cognitively active during the task, or the significant results were artifacts that could be explained by the multiple comparisons problem. Normally, when using living subjects in psychological experiments, the existence of artifacts can be explained by the experimental subject's head movements or technological failures, but Bennett et al. aim to show that also an improper statistical analysis can generate artifacts. When reminding that fMRI compares approximately 138.000 voxels, the likelihood of false positives is extremely high in research in the cognitive neurosciences that uses fMRI. When no statistical analysis correcting for this problem is applied, brain scans thus falsely display red dots that indicate brain activity. Only when interpreters of brain scans are aware that they are confronted with phenomenotechnical realizations, it becomes possible to establish a critical relation with the practice and results of cognitive neuroscience. That is, only in this way can it be understood *why* the outcome of an object that is the product of mathematical relations can be mistakenly be taken to show brain activity in a dead salmon.

In the above example, revealing how scientific objects are the product of phenomenotechnical construction allows to reveal which existing scientific principles (such as the application of proper statistical analysis) need to be in place in order for a practice to function as a scientific practice. At the same time, what are the existing scientific principles—e.g., what is considered to be a *proper* statistical analysis—is itself dynamically constituted in the relation with the objects that are realized through the phenomenotechnique. The awareness of and reflection on these principles coincides with engaging in a rational apodicticity that allows for establishing a relation with the noumenal plain in which the objects of a scientific discipline are realized. Accordingly, the realization of human cognition in scientific practice is the product of a continuous re-integrating of the rational and technical aspects of its phenomenotechnical realization. What this points to is that a philosophical analysis of scientific practice should be one in which the mathematical aspects that shape how scientific objects are realized are included. For example, without taking into account that the realization human cognition requires the presence of a mathematical plane into which experimental results are integrated, the complexity of the phenomenotechnique within which the object 'human cognition' is realized cannot be appreciated.

5. CONCLUSION

Let me move back to the question posed at the start of this paper, and ask how Bachelard's philosophy can help us answering the question how the 'rational' and the 'practical' are integrated in scientific practices? Bachelard's notion of phenomenotechnique is crucial when connecting the rational and the practical. Introducing this notion has at least three different implications. Firstly, the realization of scientific objects is dependent on performing practical actions in relation with technologies. Secondly, the phenomenotechnique creates a rational plane—Bachelard's noumenon—in which the complexity of scientific objects comes into being. Thirdly, the phenomenotechnique helps constituting a scientific city in which the epistemological obstacles grounded in the primitive experiences of individual scientists can be suppressed.

When considering these three different implications of approaching scientific objects as realized within a phenomenotechnique, it appears that the practical and the rational aspects of scientific practice are integrated in the realization of increasingly complex objects. The practical actions—for example in scientific experiments—are structured by a rational apodicticity, but the complexity created by such actions at the same time challenge existing standards of rationality. Bachelard maintains that we should understand the rationality of the scientific project in terms of the way it is realized in the latest scientific developments, and that epistemology should incorporate this form of rationality. Taking into account the insight that scientific objects are phenomenotechnical realizations, an epistemology inspired by Bachelard allows to connect (i) the practical actions that scientists perform in relation with technologies, (ii) the rational apodicticity that allows to integrate a complexity that is revealed within scientific practice into a scientific object, and (iii) the way a socio-material environment is realized that supports the rationality of the phenomenotechnique.

The ongoing re-realization of scientific objects within the scientific project not only points to the interrelation of the practical and the rational on a micro-level, but also to ongoing changes on the socio-material level. By considering the rationality within the phenomenotechnique on a micro-level, Bachelard's epistemology allows to develop a framework for the organization of the scientific city. For example, our discussion of the 'dead salmon' in §5 suggests that the realization of human cognition *as* a scientific object strongly depends on how it can be mathematically realized. This suggests that scientific *subjects* should be able to critically reflect on whether these mathematical realizations conform to their existing concepts of human cognitive functions. The phenomenotechnical realization of human cognition should therefore be accompanied with the realization of a socio-material environment in which the complexity of the phenomenotechnique can be appreciated. Accordingly, looking at the structure of the phenomenotechnique not only allows us to study the realization of scientific objects on a micro-level, but also to find a starting-point for how the socio-material environment in which science takes place could be rationally organized.

NOTES AND ACKNOWLEDGMENTS

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1. Gaston Bachelard, *The Formation of the Scientific Mind: A Contribution to a Psychoanalysis of Objective Knowledge*. Trans. Mary McAllester Jones. Manchester: Clinamon Press, 2002, 70.

2. In the French (continental) philosophical tradition, no strict distinction between 'epistemology' and 'philosophy of science' is made. In this paper, I will use these terms interchangeably.

3. See: Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge: Harvard University Press, 1987, 2-6.

4. Other examples are: Karin Knorr-Cetina, *Epistemic Cultures: How the Sciences Make Knowledge*. Cambridge: Harvard University Press, 1999, Andrew Pickering, *Constructing Quarks: A Sociological History of Particle Physics*. Chicago: University of Chicago Press, 1999.

5. Bruno Latour & Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (2nd edition). Princeton: Princeton University Press, 64.

6. Notable Exceptions are: Teresa Castelao-Lawless, "Phenomenotechnique in Historical Perspective: Its Origins and Implications for Philosophy of Science." *Philosophy of* Science 62:1 (1995, 44-59), Alfred Nordmann, "From Metaphysics to Metachemistry" *Philosophy of Chemistry: Synthesis of a New Discipline*. Eds Davis Baird, Eric Scerri, & Lee McIntyre. Dordrecht: Springer, 2006, 347-362, Hans-Jörg Rheinberger, "Gaston Bachelard and the Notion of 'Phenomenotechnique.'" *Perspectives on Science* 13:3 (2005, 316)

7. Bachelard, *The Formation of the Scientific Mind*, 28.

8. Bachelard, *The Formation of the Scientific Mind*, 33.

9. The idea that our immediate encounter with reality is grounded in our primitive drives is why Bachelard occasionally refers to his project as a psychoanalysis of knowledge. See for example: Gaston Bachelard, *The Psychoanalysis of Fire*. Trans. Alan C.M. Ross. London: Routledge, 1964. A detailed analysis of this aspect of Bachelard's philosophy is beyond the scope of this paper. For an excellent discussion on this topic, see for example: Cristina Chimisso, *Gaston Bachelard: Critic of Science and Imagination*. London: Routledge, 2013, 181-218.

10. Gaston Bachelard, *Water and Dreams: An Essay on the Imagination of Matter*. Trans. E.R. Farrell. Dallas: The Pegasus Foundation, 1999, 5.

11. Gaston Bachelard, *Water and Dreams*, 7.

12. Gaston Bachelard, *The Philosophy of No*. Trans. G.C. Waterson. London: Routledge, 1968, 9.

13. See: Bachelard, *The New Scientific Spirit*, 135-177. For an extensive discussion of Bachelard's non-Cartesian epistemology, see: Mary Tiles, "Technology, Science, and Inexact Knowledge: Bachelard's Non-Cartesian Epistemology" *Continental Philosophy of Science.* Ed Gary Gutting. Oxford: Blackwell, 2005, 157-175.

14. René Descartes, *Meditations on First Philosophy 3rd Edition*. Trans. D.A. Cress. Indianapolis: Hackett Publishing Company, 1993, 21.

15. Gaston Bachelard, *The New Scientific Spirit*. Trans. Arthur Goldhammer. Boston: Beacon Press, 1984, 171.

16. Bachelard, *The New Scientific Spirit*, 3.

17. Bachelard, *The New Scientific Spirit*, 3.

18. See, Bachelard, *The New Scientific Spirit*, 6.

19. Bachelard, *The Formation of the Scientific Mind*, 70.

20. Gaston Bachelard, *L'Activité Rationaliste de la Physique Contemporaine*. Paris: PUF, 1951, 10.

21. Gaston Bachelard, "From La Essai Sur la Connaissance Approchée. Trans. Mary Tiles" *Continental Philosophy of Science*. Ed Gary Gutting. Oxford: Blackwell, 2005, 180.

22. Bachelard, "From La Essai Sur la Connaissance Approchée," 176.

23. Bachelard, "From La Essai Sur la Connaissance Approchée," 181.

24. Descartes made this distinction to make clear that his doubt was a methodological asset in his search for certain and indubitable knowledge, but should not be without hesitation be transferred to the domain of practical action. See: Descartes, *Meditations*, 16.

25. Rheinberger, "Gaston Bachelard and the Notion of 'Phenomenotechnique'," 316.

26. Bachelard, *The New Scientific Spirit*, 1.

27. Gaston Bachelard, *Le Rationalisme Applique*. Paris: PUF, 1951, 5.

28. An excellent discussion of these concepts can be found in: Hans-Jörg Rheinberger, *An Epistemology of the Concrete: Twentieth-Century Histories of Life*. Durham: Duke University Press, 2010, 25-37.

29. Gaston Bachelard, 'Noumenon and Microphysics,' trans. Bernard Roy. *Philosophical Forum* 36:1 (2006, 79).

30. Bachelard, *The New Scientific Spirit*, 143.

31. See: Cristina Chimisso, 'From Phenomenology to Phenomenotechnique: The Role of Early Twentieth-Century Physics in Gaston Bachelard's Philosophy.' *Studies in History and Philosophy of Science Part A* 39:3 (2008, 387).

32. Bachelard, *Le Rationalisme Applique*, 121, trans. by author.

33. This implies that scientific theories or paradigms can never be fully discontinuous , as each new scientific theory necessarily develops in interaction with the erroneous scientific judgments that it aims to overcome. Despite their seeming similarities, it is on this point that Bachelard's epistemology significantly differs from the Kuhnian notion of paradigm. See: Thomas Kuhn, *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1962. For further discussion on the relation between Bachelard and Kuhn, see for example: Stephen W. Gaukroger, "Bachelard and the Problem of Epistemological Analysis." *Studies in History and Philosophy of Science* 7:3 (1976, 189-244), Dominique Lecourt, *Marxism and Epistemology: Bachelard, Canguilhem and Foucault*. Trans. Ben Brewster. London: NLB, 1975, 7-19. For an in-depth discussion of the mutual influence of Kuhn's work and French epistemology, see: Massimiliano Simons, "The Many Encounters of Thomas Kuhn and French Epistemology." *Studies in History and Philosophy of Science Part A* 61 (2017, 41-50)

34. See: Bachelard, *The Formation of the Scientific Mind*, 20.

35. See: Rheinberger, "Gaston Bachelard and the Notion of 'Phenomenotechnique'," 315.

36. Bachelard, *The Formation of the Scientific Mind*, 13.

37. Bachelard, *Le Rationalisme Applique*, 119-21.

38. For an extensive discussion of Bachelard's notion 'scientific city,' see: Cristina Chimisso, *Gas-*

ton Bachelard: Critic of Science and Imagination, 198-201.

39. The claim that cooperation between scientists is typical for 20th century science can be doubted on historical grounds. For an account of the cooperation in the 17th century between scientists (natural philosophers) and the need for experiments to be public events to be observed by other scientists, see for example: Lorraine Daston and Peter Galison, *Objectivity*. New York: Zone Books, 2007. Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life 2nd Edition*. Princeton: Princeton University Press, 2011.

40. Gaston Bachelard, *Fragments of a Poetics of Fire*. Trans. Kenneth Haltman. Dallas: The Pegasus Foundation, 1997, 9.

41. See: Bachelard, *L'Activité Rationaliste de la Physique Contemporaine*, 6-7.

42. See for example: Adina L. Roskies. "Are Neuroimages Like Photographs of the Brain?" *Philosophy of Science* 74 (2007, 860-872).

43. The Ig Nobel Prizes are a counterpart to the Nobel Prizes, and are awarded to "achievements that first make people laugh and then make them think." See: Improbable Research. "About the IG ® Nobel Prizes." Accessed September 12, 2017. http://www.improbable.com/ig/

44. Craig M. Bennett et al., "Neural Correlates of Interspecies Perspective Taking in the Post-Mortem Atlantic Salmon: An Argument For Proper Multiple Comparisons Correction," *Journal of Serendipitous and Unexpected Results* 1:1, (2010, 2).