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TWO STYLES OF REASONING IN SCIENTIFIC PRACTICES: EXPERIMENTAL AND MATHEMATICAL TRADITIONS

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Abstract

This article outlines a philosophy of science in practice that focuses on the engineering sciences. A methodological issue is that these practices seem to be divided by two different styles of scientific reasoning, namely, causal-mechanistic and mathematical reasoning. These styles are philosophically characterized by what Kuhn called 'disciplinary matrices'. Due to distinct metaphysical background pictures and/or distinct ideas on what counts as intelligible, they entail distinct ideas on the character of phenomena and what counts as a scientific explanation. It is argued that the two styles cannot be reduced to each other. At the same time, although they are incompatible, they must not be regarded as competing. Instead, they produce different kinds of epistemic results, which serve different kinds of epistemic functions. Moreover, some scientific breakthroughs essentially result from relating them. This view on complementary styles of scientific reasoning is supported by pluralism about metaphysical background pictures.

1. Introduction

'Philosophy of science in practice' can be understood in two different ways: first, as 'philosophy of science *of* scientific practice', and second, as 'philosophy of science *in* scientific practice'. The mission statement of the *Society for the Philosophy of Science in Practice* (SPSP, 2006), proposes ideas about its own subject matter, aims and methods, which cover the two meanings. 'Scientific practice' is accounted for in terms of a tripartite relationship between knowledge (e.g., data, descriptions of phenomena, explanations, theories, and scientific models), world (including scientific instruments and experiments as well as the phenomena produced by them), and cognitive agents who perform epistemic activities in that practice. Furthermore, 'philosophy of science *of* scientific practice' deals with philosophical problems that originate from scientific practices. For example, the conceptual and methodological issues related to complexity, interdisciplinarity, and the use of (new) technologies and methods like sophisticated instrumentation and computer simulations. Additionally, it deals with epistemological issues related to the applicability of scientific results that concern practical, societal or ethical matters. 'Philosophy of science *in* scientific practice', in turn, aims to make contributions to research practices by bringing philosophical findings back to the practice, for instance by contributions to science teaching or scientific research projects.

My endeavour is developing a philosophy of science for the engineering sciences that is firstly beneficial for epistemic activities of scientific researchers. This implies providing materials for philosophy of science *in* scientific practices. My approach is to analyse issues relevant to these practices by employing concepts and ideas of the philosophy of science in ways that are significant and intelligible for practitioners and philosophers of science. Thereby, I also aim to promote productive exchange between these two academic fields.

The aim of this paper is analyzing a specific methodological issue that I have encountered as relevant for a practicing scientist. The issue is that specific practices are often dominated by one of the following two approaches. Firstly, fundamental approaches such as those presented in physics textbooks, which focus on constructing mathematical models of a physical system or phenomenon by building on fundamental laws. Secondly, experimental approaches, which, conversely, often focus on the construction of causal-mechanistic models of the phenomenon under study by employing phenomenological and causal knowledge. This situation can be interpreted as an exemplification of scientific pluralism (e.g., Kellert *et.al.* 2006, Mitchell 2009), scientific perspectivism (Giere 2006) and/or metaphysical nomological pluralism (Cartwright 1999). Although I am sympathetic to these pragmatic accounts of plurality in actual scientific practices, they are not fully satisfactory when considering specific difficulties arising from methodological plurality that practitioners are facing. Alternatively, the view presented in this article may be regarded as a substantiation of Michael Lynch's (1998) metaphysical pluralism. The core of Lynch's metaphysical pluralism is the idea that the world is tolerant of more than one single description as there can be a plurality of incompatible but equally acceptable conceptual schema's in terms of which we describe nature.[1]

My starting-point is the idea is that metaphysical background pictures always guide practitioners in constructing scientific explanations (cf. Kuhn 1970, Dear 2006), that is, metaphysical ideas guide and enable conceptualizing how the world is. However, practitioners sometimes tend to understand scientific explanations based on incompatible background pictures as competing, and to see one as primary while others are derivative. Fundamental and experimental approaches, for instance, involve mutually incompatible metaphysical ideas. My conjecture is that realist readings of them are partly (and implicitly) responsible for the situation that many practices favour only one of these approaches. At the same time, the ability of combining fundamentally different approaches has been responsible for important scientific breakthroughs. Therefore, scientific practices may advance if they could intellectually accept incompatible background ideas.[2]

2. The engineering sciences: Scientific modelling of phenomena

My subject is the engineering sciences. Elsewhere, I have proposed a distinction between *engineering sciences* and *engineering* (Boon 2006, forthcoming a). The latter is a practice concerned with creating, producing, improving, controlling and/or designing technological materials, processes and apparatus. The *engineering sciences* is a scientific practice that primarily aims at (re-)producing, (artificially) creating, improving, controlling, eliminating, or otherwise intervening with phenomena that supposedly determine technological (dis-) functioning of technological artefacts, by means of experimentation, instrumentation and scientific modelling of these *phenomena* brought about by technological artefacts.

Hence, part of the job of scientific researchers in the engineering sciences is to construct scientific models of phenomena. This includes the modelling of aspects of technological devices, in particular, of how they produce a phenomenon of interest. These phenomena are either well established or merely conceptualized and subject of technological creation. Scientific models are constructed for epistemic purposes such as conceptual, causal, phenomenological, causal-mechanistic and/or mathematical reasoning about technological artefacts. These models are then used to study the improvement of performances of technological artefacts in terms of interventions with (dis)functional phenomena.

Usually, scientific models present causal-mechanistic and/or mathematical explanations of phenomena (Boon 2006). In the engineering sciences, scientific models often also incorporate dimensions of typical configurations of devices that produce the phenomenon, which is represented in so-called diagrammatic models (Boon 2008).

Furthermore, models are related to the real world by means of measurable physical variables (e.g., in the case of phenomena relevant to chemical engineering: chemical affinities, fluid-flow rates, temperature, and specific properties of materials such as density, diffusivity, viscosity and thermal conductivity). One of the main epistemic purposes of the engineering sciences, therefore, is developing scientific models that function as epistemic tools which enable scientific reasoning about creating or intervening with technologically relevant phenomena and/or the technological artefacts that produce them (Boon and Knuuttila 2009).

The engineering sciences do not differ from the natural sciences in their attempts to understand phenomena that either occur naturally or are produced technologically. Also, the ways in which phenomena are produced, studied and modelled are not significantly different. Significant differences between the two practices are the role attributed to phenomena of interest and the epistemic purposes of scientifically modelling them. In the natural sciences, phenomena, and their descriptions and scientific models usually are considered as the gateway to knowing how the world is. In the engineering sciences, these elements are firstly crucial for intervening with the world. Physical phenomena and measurable variables brought about by a physical system are means for physical interventions. Phenomenological descriptions and scientific models of phenomena provide epistemic tools that enable scientific reasoning about how to produce physical systems for specific purposes.

Below, I will make use of the fact that the functioning of a physical system can be characterized in terms of different kinds of phenomena, namely, physical phenomena and patterns of measured variables.[3] Scientists may build a device such that it produces or, conversely, prevents the occurrence of a physical phenomenon. Alternatively, we may intervene with the system by means of changing or controlling one or more measurable variables, such as temperature, in order to produce the desired data-pattern. I will refer to the physical system as the *target system,* which may be approached as a specific type, such as mechanical, chemical, biological, biochemical and/or electrical systems, depending on the specialization of a scientific practice. Descriptions and scientific models of different kinds of phenomena, therefore, enable predicting the behaviour of a target system, as well as scientific reasoning about possible interventions with it.

In current scientific practices, causal-mechanistic *and* mathematical approaches may take part productively in the development of scientific models of the phenomena that characterize the functioning of a target system. It often appears however, that scientific practices are dominated by only one of these modelling types. Some scientists believe that models derived from fundamental theories is what science must aim at, while others hold that such models are limited and that we need to understand the causes or the causal-mechanism in order to really understand the target system.

Two movements that make possible analysing this issue from a ‘philosophy of science in practice’ perspective are firstly, the so-called new experimentalism (Ackermann 1989). This movement defends that accounts of science should reflect how experimental knowledge is actually arrived at in practice (e.g., Hacking 1983, 1992, Ackermann 1985, Franklin 1986, Galison 1987, Gooding et.al. 1989, 2002, Cartwright 1989, Baird and Faust 1990, Mayo 1996, Radder 1996, 2003, Harré 1998, 2003, Steinle 2002, Heidelberger 2003, Chang 2004). In my approach, this includes how scientists reason about experiments, instruments, and data, and about the adequacy and applicability of theoretical knowledge to a concrete target system. The second movement consists of authors who have turned focus away from scientific theories, emphasizing the role of scientific modelling in scientific practices (e.g., Hesse 1966, Cartwright 1983, 1999, Giere 1988, 1999, 2004, Morrison 1999, Morrison and Morgan 1999, Suarez 1999, 2003, Frigg 2002, Knuuttila 2005, Weisberg 2007, Bailer-Jones 2009). Significant with regard to the engineering sciences is the idea that models are not exclusively justified by means of experimental tests but that part of their justification is ‘built-in’ the model (cf. Boumans 1999), and the idea that models are first and foremost epistemic tools that enable and guide scientific thinking about interventions with aspects of the world, and about technological creation of phenomena for new functions (Boon and Knuuttila 2009).

Addressing the issue of distinct modelling practices is relevant for scientific practices given that scientific breakthroughs often come about when a practice succeeds in combining different kinds of scientific modelling. An example is the modelling of biochemical pathways, which, until the 1980’s was predominantly tackled by causal-mechanistic reasoning grounded in biochemistry. Based on scientific knowledge in this field, models of pathways were proposed and experimentally tested (e.g., by the use of labelled molecules in biochemical measurements). Scientific researchers such as J.A. Roels (1983), proposed (in my terminology) to combine the typical causal-mechanistic approach of constructing models of biochemical-pathways, on the one hand, with mathematically modelling these pathways in terms of the fundamental laws of thermodynamics and measurable thermodynamic properties, on the other. This integrated approach has led to an enormous step forward in explaining, predicting, discovering and creating biochemical pathways in specific target systems such as enzymatic systems, bacteria, human bodies, environmental systems and industrial processes. Some of the predicted pathways had not been discovered prior to this advancement, but were found in nature once their physical possibility had been predicted. Additionally, by means of mutually related causal-mechanistic and mathematical modelling, models were constructed that could be utilized as epistemic tools in reasoning about how to create such pathways by technological interventions. This new tandem approach to the construction of models of biochemical systems enabled many of the important developments in biotechnology today.

In this article I aim to address the following findings observed in scientific practices: (a) scientific practices are capable of producing distinct types of scientific models of the same target system, such as models presenting causal-mechanistic explanations of its behaviour versus models that present mathematical interpretations, (b) scientific practices often focus on only one type of scientific modelling approach – usually this preference is related to whether a practice is experimentally or mathematically oriented, which often coincides with a causal or causal-mechanistic versus a fundamental or mathematical orientation in modelling, (c) philosophically, this preference may have to do with philosophical presuppositions of 'real' or 'good science', which in turn may involve metaphysical presuppositions that are taken as true, (d) scientific research may produce models that are more productive in scope, generality, reliability, specificity, applicability, predictive power and creative possibilities when scientists are capable of constructing different types of models in a mutual interaction, (e) different types of scientific models enable different kinds of epistemic uses, that is, causal-mechanistic models enable other ways of scientific reasoning about a target system than mathematical models, and (f) from a scientific practice point of view, there is no point in claiming that different types of scientific models of the functional phenomenon produced by a target system, are reducible to each other – neither that they are essentially isomorphic nor that it would be preferable (or scientifically more outstanding) to reduce them to each other.[4]

3. Causal (or causal-mechanistic) versus mathematical (or 'fundamental') interpretations of phenomena

In early philosophy of science literature, the difference between types of laws, and later, types of models, has been neglected or denied. This is most obvious in the work of authors in logical positivism and logical empiricism such as Carl Hempel, Thomas Nagel, and Karl Popper, but still in Bas Van Fraassen and Ronald Giere. Clearly, this denial has to do with attempts to avoid mention of causal relationships in philosophical accounts of the justification of scientific knowledge. In more recent debates, the difference between scientific explanations in terms of causal and fundamental laws has been acknowledged, but rather than considering them as complementary as I will propose in this article, the difference has become subject to dispute on priority. Defenders of causal explanations, such as Michael Scriven (1975), Wesley Salmon (1985) and Jim Woodward (2003, 2003a), and similarly, of explanations in terms of theoretical entities (Hacking 1983) and capacities of nature (Cartwright 1989), are inclined to argue that causal explanations have priority whereas general (mathematical) laws are parasitic on causal explanation of individual events. Against this causalist view, defenders of the so-called unificationist view of explanation, such as Michael Friedman (1974) and Philip Kitcher (1976, 1981), have argued that scientific explanation consists of reduction of phenomenological laws to more fundamental laws which makes causal laws derivative. On this latter account, scientific explanation consists of showing that apparently disparate phenomena can be shown to be fundamentally similar.

Salmon (1990, 2002), in response to the battle of priority, attempts to reconcile the two by arguing that they are complementary. To do this, he presents two elegant examples which illustrate that a causal explanation (or prediction) of an event and an explanation (or prediction) of the same event in terms of fundamental laws, yield exactly the same outcome.[5] Although the unificationist account of scientific explanation does not necessarily coincide with explanations in terms of fundamental theories, Salmon's examples suggests that this is what is at stake, which makes this discussion relevant to my issue. Salmon, however, is not entirely clear about what he means when saying that causalist and unificationist explanations are complementary.

In my practice-oriented view, I propose that the two are complementary as follows. In scientific practice, concurrent utilization of two (or more) ways of both phenomenologically describing, and scientifically explaining or theoretically interpreting phenomena may yield better epistemic results in scope, generality, reliability, specificity, applicability, predictive power and creative possibilities (e.g., for reasoning about interventions with the target system). Exclusive use of only one approach often yields limited epistemic results, as I have illustrated with the example from biochemistry.

My aim is to make plausible that from a scientific practice point of view it is unproductive to believe (e.g., to maintain as a normative presupposition or 'best supported' metaphysical belief) that different types of laws and models are essentially equal or isomorphic, or that, in principle, they are reducible to each other or stand in a hierarchical relationship. To the contrary, I claim, it is important to distinguish between different types of scientific laws and models, and to gain understanding of their diverse functions as epistemic tools in scientific practice, and how or why using different possibilities of ‘structuring and conceptually interpreting’ the world is crucial to scientific advances.

The philosophical question I aim to address is why there are different types of scientific laws and models, and why they should not be seen as (in principle or ideally) reducible to each other. Why, instead, must they be valued as complementary, both in enabling their simultaneous construction and in their subsequent simultaneous functioning as epistemic tools? My short answer is because the same target system (e.g., a physical event, material, process or apparatus) can be interpreted in different ways, both regarding the *kind* of phenomenon that characterizes the target system (i.e., the phenomenon that is supposed to produce or determine its proper or improper functioning), and regarding the *kind* of theoretical interpretation of the phenomenon.

To exemplify this, let us first suppose that we have a specific, concrete target system for example, a chemical conversion process, or a magnet moving in an electricity-conducting coil, or yeast cell in bread dough. It is important to see that the (description of the) target system does not coincide with (the description of) the phenomenon of interest. The first thing to do in the mentioned scientific practices is discerning or determining the phenomenon of interest that characterizes the (dis)functional behaviour of the target system. Examples of such phenomena are respectively, the production of a specific chemical product, the production of electrical current, and the production of carbon dioxide and heat. Next, scientific researchers aim to produce epistemic tools that enable them to think about, e.g., creating or intervening with the phenomenon of interest, often by means of direct interventions with the target system. They do this by constructing scientific laws or models of phenomena they have discerned as relevant to the functioning of the target system. The laws or models, in turn, must function as epistemic tools for thinking about interventions with the phenomenon. Accordingly, the first ‘interpretative’ activity is to see the target system in terms of a specific *type* of phenomenon. Subsequently, scientists construct theoretical interpretations (e.g., causal or mathematical explanations) of the phenomenon, thus producing scientific laws or models of it.

Scientific research in these practices, therefore, does not start at the level of phenomena that somehow interest us, but at the level of concrete target systems (e.g., natural systems or technological devices, materials and processes) that we want to create, intervene with, or predict the behaviour of. What’s more, a target system does not tell us what to take as the phenomenon that characterizes it or ‘asks for’ a theoretical interpretation. Instead, ‘seeing’ or discerning a phenomenon involves an interpretative activity already. This interpretive activity is usually guided by the kinds of theoretical approaches we have at our disposal (also see Massimi 2008). My point is not that observation is theory-laden, but alternatively, that certain ‘styles of scientific reasoning’ as I will call them (that is, types of theoretical approaches such as causal-mechanistic or mathematical approaches), enable us to ‘see’ or discern specific types of phenomena. Thus, the style of reasoning employed also determines or guides the way in which the phenomenon will be theoretically interpreted (also see Boon 2009, Boon and Knuuttila 2009).

As a consequence, a relevant (e.g., functional) aspect of a target system may be accounted for in terms of different kinds of phenomena, the theoretical interpretations of which bring forth different kinds of scientific laws and/or models. These laws and models are different kinds of epistemic tools with which researchers can perform different kinds of epistemic tasks.

Let us take as an example of a target system the production of alcohol by yeast cells in grape juice. A causal phenomenon of interest that determines the functioning of this target system is that yeast cells convert sugar in alcohol and carbon dioxide. This *physical phenomenon* can be studied in a specific experimental set-up. In an extended set-up, researchers may keep track of supposedly relevant measurable variables such as sugar and alcohol concentration, number of yeast cells, amount of consumed oxygen and produced carbon dioxide, temperature, acidity, liquid volume, etc. I propose to regard the (dynamical) relations between measured variables as another type of phenomenon, which I will call a *mathematical phenomenon* because these relations are described by mathematical formula. Hence, when studying a target system by means of experimental interventions and specific types of measuring instruments, practitioners construct *descriptions* of physical phenomena (e.g., “the conversion of sugar to alcohol and carbon dioxide by yeast”) and of mathematical phenomena (e.g., “the conversion rate of sugar is proportional to the production rate of carbon dioxide” or, “this formula represent the relations between measured variables A, B, …”). The physical phenomenon is usually described in terms of phenomenological or causal relationships. A theoretical interpretation of it may consist of a causal-mechanism, for instance, of how yeast cells do this in terms of biochemical pathways. Mathematical formula describing a relation in a set of measured variables usually also include variables and parameters that have not been measured directly, but instead, are produced by specific theoretical methods of relating measured variables. In scientific practice, such formulae also are called phenomenological (or empirical) descriptions. Their theoretical interpretation is a mathematical model, which is constructed in terms of more fundamental laws such as the laws of thermodynamics.

The physical and mathematical phenomena characterize (approximately) the same functional aspect of the target system. At the same time, the causal-mechanistic model and the mathematical model are distinct theoretical interpretations of two different phenomena, that is, of two different kinds of phenomenological descriptions of the functioning of the target system. Although these two types of models can be mutually related, and may even have been constructed in a mutual interaction, they are essentially different. Practitioners often restrict themselves to only one of these approaches. If they focus on the physical phenomenon brought about by the target system, and exclusively aim to explain it in terms of, e.g., biochemical path-ways, they neglect the mentioned mathematical phenomenon and explanations in terms of fundamental laws, vice versa.

4. Styles of Scientific Reasoning.

My approach to developing a philosophical account of this issue in scientific practice in ways that also speak to practitioners, finds part of its ideas in the tradition of integrated history and philosophy of science. The idea that the same event can be scientifically explained in different ways is accounted for by Thomas Kuhn's (1970) insight that creating the kinds of scientific explanations that are accepted as explanatory by scientists in a specific era, usually involves a metaphysical background picture of what the world is like. Besides other things (e.g., other aspects of what Kuhn calls a disciplinary matrix), a metaphysical background picture guides and constrains which kind of phenomena are picked out, and what kind of explanations or interpretations are regarded as meaningful and significant. This latter view has been fleshed out by authors who also work in this fringe area of the history and philosophy of science such as Crosbie Smith (1989) and Peter Dear (2006). Kuhn (1970) suggested, or at least was understood this way, that metaphysical background pictures (as part of disciplinary matrices as a whole) follow up on each other. They emerge and disappear in scientific revolutions. Authors such as A.C. Crombie (1995), John Pickstone (2000) and Chunglin Kwa (2011) are less radical. They have proposed distinctions between *styles of scientific reasoning* in the history of science, without explicitly claiming that these styles overrule each other. Following up on their ideas, I propose that styles of scientific reasoning can productively co-exist, even in the same scientific practice. Nevertheless, styles of scientific reasoning and their radical changes significantly involve (radically changing) metaphysical background pictures, which still points at Kuhn's notion of 'disciplinary matrices'.

The consequences drawn from the 'styles of scientific reasoning' account of changing metaphysical ideas in the history of science may be less disturbing than those inferred from Kuhn's initial insight. Briefly put, Kuhn's insight landed in a theory-oriented view of science. In this context, the indispensable role of metaphysical background ideas has been taken as devastating to the epistemic value of theories as it seems to make science subjective and irrational. A 'styles of scientific reasoning' account of science, conversely, turns focus to the character of scientific reasoning, which involves accepting a three-placed relationship between knowledge, world and cognitive agent, rather than the traditional two placed relationship between theories and world that excludes the role of scientific reasoning. What's more, this 'styles of reasoning' account draws attention to the idea that science *enables thinking about the world* (or, target systems) – for instance, making predictions about future states, or creative thinking about interventions with a target system. Accordingly, in a 'styles of reasoning' account, metaphysical background pictures enable and guide the construction of scientific theories (or, more general, epistemic results, which includes descriptions of phenomena, and scientific laws, models and concepts). Or, as Lynch (1998) suggests, they provide fundamental conceptual schemes in terms of which, in my vocabulary, descriptions of observations and theoretical interpretations are articulated. Smith (1989) and Dear (2006) present clarifying examples of this crucial role of (changing) metaphysical background pictures in the development of science.

The actual situation of scientific practices is better explained by assuming that 'pictures' and 'styles' often continue to be utilized, rather than assuming that new, successful metaphysical background pictures and styles of reasoning overrule and cancel out their predecessor. Therefore, I take the following view as a preliminary of my further approach: metaphysical ideas are crucial as they enable and guide the construction of theoretical interpretations of target systems as well as the articulation of phenomena that are theoretically interpretable. Moreover, incompatible metaphysical ideas are not necessarily competing. Instead, they may very well appear to be complementary. This 'styles of scientific reasoning' account takes metaphysical ideas as 'tools for thinking about the world', that is, as ways to picture, articulate and conceptualize aspects of the world (also see Rouse 2009).

Yet, my approach is different from authors who took integrated history and philosophy of science approaches (e.g., such as Kuhn, Smith, Crombie, Dear, Pickstone, and Kwa), as I do not aim to make historical claims. I do not aim to defend that there are actually two distinct traditions as Kuhn (1977) does; nor do I strive to describe how scientists *actually* thought and did their scientific work. Instead, my aim is to provide systematic ideas that may contribute to current scientific practices.

By distinguishing between experimental and mathematical approaches in current scientific practices, I aim to make plausible that scientific practices have at their disposal different ways of conceptualizing the world (or target system). Focus on the role of conceptualization in science agrees to a recent school of thought in integrated history and philosophy of science that puts emphasis on the role of conceptualization in observation and measurement (e.g., Chang 2004, Massimi 2009, Rouse 2009), and on the formation of scientific concepts (e.g., Feest 2008, Nersessian 2008, Steinle 2006). Additionally, my aim is making plausible that incompatible metaphysical ideas, which prompt fundamentally different ways of conceptualizing the world both on the level of phenomena and on the level of their theoretical interpretations, does not point to the necessary incorrectness of at least one of these ideas. Instead, the actual occurrence of the two approaches exemplifies that more than one way of conceptualizing the world is possible (cf. Lynch 1998). Moreover, these different ways (or styles of reasoning) are not excluding each other. Instead, they often can be complementary, especially in order to improve our epistemic tools.

Kuhn (1977) presents a historical distinction between an experimental and a mathematical tradition in the development of the physical sciences. From a philosophical perspective, I consider these traditions as two styles of reasoning that entail distinct metaphysical background ideas. The aim of Kuhn's article was presenting historical causes of the *Scientific Revolution*, such as the new intellectual ideas and milieu, which, according to him, were important for the development of the mathematical and the experimental tradition. Kuhn makes clear that distinct approaches not only involve differences in their 'material' and 'technological' aspects (such as the role of experimental and mathematical techniques), but also that intellectual ideas about important aspects of scientific practice, such as the character of phenomena, the ontology of its subject matter, the character of scientific explanation and fundamental laws, ideas about scientific methods, and metaphysical ideas about the character of scientific theories, hang together.

Kuhn's notion of 'disciplinary matrices' (1970) may be useful in articulating the distinction between experimental and mathematical traditions, although Kuhn (1977) does not explicitly mention this. A disciplinary matrix consists of 'background' and epistemological values, a metaphysical picture of the world, core principles, scientific methodology, and exemplars. The notion of distinct disciplinary matrices in its commonly accepted meaning, may explain some of the epistemological difficulties that arise when trying to account for the complementarities of distinct scientific approaches. Below, I will propose an alternative reading of this important notion, as its common meaning has yielded at least two unproductive implications, namely: (a) in Kuhn's conception, practices that are built upon distinct disciplinary matrices produce incommensurable scientific theories, which are theories that cannot be compared to a common standard – an implication which has been taken as an argument that theory choice is neither rational nor objective, and (b) diverse disciplinary matrices determine specific scientific approaches that are distinct to such an extent that scientific researchers can agree to only one.

Behind the first implication is the idea that we must always choose between evidently competing theories. This idea is correct if a theory is logically inconsistent or empirically inadequate in relevant respects (which are both good reasons for aiming to discard a theory – even after Kuhn), but not in the case of incommensurability between theories. Scientific results are constructed within a specific conceptual scheme, and their rational acceptability or truth is to be evaluated within that scheme (Putnam 1981, Lynch 1998). Different theoretical interpretations of the same target system (that is, utilization of different metaphysical ideas in scientific approaches to the same target system) may enable us to perform different kinds of epistemic tasks. From a practice oriented point of view, distinct scientific approaches produce various kinds of epistemic tools, which allow for different, possibly complementary ways of reasoning about a target system.

Regarding (b), we may wonder why scientists are only capable of agreeing to one kind of approach or, why they are expected to behave this way. One reason might be an interpretation of scientific theories as being true descriptions of reality, which in combination with the idea that only one description can be true, makes them to adopt metaphysical background ideas not just as a 'tool for thinking' but as 'real'. This presupposition forbids juggling with metaphysical ideas that are incompatible – a situation that forces them to choose the 'best supported' or most plausible belief. Another reason may be, sometimes suggested by Kuhn, that juggling with incommensurable disciplinary matrices is intellectually too demanding – in that case, choosing one approach has to do with personal preferences, intellectual capacities and scientific education. Nevertheless, some scientists are capable of utilizing different approaches in a mutual interaction.

The historical occurrence of (at least) two distinct scientific traditions – of which the distinctness is philosophically accounted for in terms of aspects that constitute disciplinary matrices – makes plausible that different styles of reasoning and kinds of theoretical interpretations are in fact possible. The experimental and mathematical approach involve incommensurable metaphysical ideas in the sense that the first understands the world in terms of physical objects and their properties, which cause the physical phenomena we observe, whereas the second holds fundamental laws responsible for observed phenomena.[6] Instead of considering them as competing, I defend that the two approaches are about the same target system, but about different kinds of phenomena.

In order to account for the possibility that different approaches can be complementary, I propose understanding scientific theories, models, laws and concepts as 'theoretical interpretations' rather than 'explanations' (also see Bailer-Jones 2009). This reading allows for recognizing the possibility for fruitful collaboration of assorted kinds of incommensurable theoretical interpretations, avoiding the idea that one must prevail over the other. Additionally, I propose to uphold Kuhn's notion of 'disciplinary matrices' as it presents us with a conceptual framework for analysing and understanding differences between styles of reasoning, yet, with the addition that metaphysical background ideas should not be taken as a true description of reality. Descriptions of phenomena as well as their theoretical interpretations are coherently constructed within the confines of a disciplinary matrix.[7] Holding that theoretical interpretations are ways of 'structuring and interpreting' the world, and further that different ways of doing so can be valued for being complementary rather than being compatible, implies that finding dissimilar kinds of ways of interpreting and structuring the world is part of the greatness of science (Boon 2009).

An obvious argument against the idea of different styles of reasoning that to some extent are autonomous and incommensurable, is the well accepted idea that the two styles have merged, e.g., since Newton's *Principia*. Below, I aim to explore in what sense they have become related, and in what sense they still must be regarded as distinct. My focus will be on differences between the kinds of phenomena and explanations characteristic of mathematical and experimental approaches.

5. Philosophical analysis of mathematical and experimental approaches.

In the philosophy of science, it is usually assumed that the notion of a phenomenon is intuitively clear. According to Ian Hacking (1983, 221), "[Phenomenon] has a fairly definite sense in the writing of scientists. A phenomenon is noteworthy. A phenomenon is discernible. A phenomenon is commonly an event or process of a certain type that occurs regularly under definite circumstances." Another aspect of a phenomenon is that it makes us curious; we want to find an explanation for it, often in the context of particular aims and uses. Yet, in actual scientific practices, practitioners are not somehow passive observers of phenomena. Instead, they "identify a phenomenon with recognizing that something has the potential to be theoretically explained" (Bailer-Jones 2009, 167). Identifying a phenomenon that has this potential is already an intellectual achievement. Therefore, I suggest that a more detailed analysis is needed of how scientists materially produce a phenomenon and of how they epistemically discern it, that is, how they come to 'see' or 'recognize' it in the midst of the manifold of observations and experimental findings. By presenting some familiar, highly simplified textbook cases of science, I aim to illustrate that the focus in the experimental approach is on discerning physical occurrences, whereas mathematical approaches focus on discerning patterns in measured (abstract and quantitative) data-sets, and furthermore, that the two kinds of descriptions of phenomena are not equivalent. Accordingly, I propose a conceptual distinction between physically and mathematically constructed phenomena, not only in the engineering sciences, but in the natural sciences in general.

In the experimental tradition, scientists focused on what I call 'physically constructed phenomena'. In the sixteenth century, William Gilbert, for instance, developed a 'terrella', a 'little earth', which is a magnetized sphere having a magnetic north and south pole. Gilbert showed that when moving a small compass around it, the needle always pointed in the north-south direction of the sphere. The physical phenomenon he thus found is that a magnetized sphere *causes* a compass-needle to always points in the same direction relative to the sphere.[8] Robert Boyle, in the seventeenth century, developed the air-pump and did experiments in which he found that forcing the increase of the volume of a fixed quantity of gas while keeping the gas at the same temperature, *caused* a decrease of the pressure of the gas. Conversely, reducing the volume of the gas caused an increase of the pressure. Antoine Lavoisier, in the eighteenth century, in his experiments on combustion of chemical substances, showed that when sulphur or phosphorus burn, there is a gain in weight that must be due to the combination with atmospheric air. Sadi Carnot, in the beginning of the nineteenth century, pointed out that wherever a difference in temperature exists, heat (caloric) flows from a hot body to a cold body until the two bodies have the same temperature. Hence, any temperature difference between bodies *causes* the flow of caloric, while caloric has the *capacity* of heating. Hans Christian Ørsted, in the nineteenth century, concluded from experiments with a magnetic needle and an electrical wire that change of voltage *causes* the rotation of the needle. Michael Faraday showed that moving a magnet through a coil of metal wire produces a voltage. He also showed that a magnetic bar held underneath a paper covered with randomly spread iron filings *causes* the iron filings to turn into patterns of circular lines, while iron filings have the *capacity* of responding to a magnetic bar. Gregor Mendel, in the mid nineteenth century, examined the inheritance of specific traits in the common garden pea. He observed that the cross-breading (hybridization) of peas harvested from white and purple flowers *produced* white and purple flowers, and in the next generation, that cross-breeding hybrid peas of white flowers produced white and purple off-spring, whereas cross-breeding hybrid peas of purple flowers only produced purple off-spring. From these experiments, he inferred that there is a complicated causal relation between the colour of parents and their offspring.

These – clearly overly simplified and from the perspective of a historian even idiosyncratic – examples show that from intervention with a physical system reproducible physical behaviour is produced which *is* the constructed physical phenomenon (also see Boon and Knuuttila 2009). Moreover, such a phenomenon can also be described in terms of physical objects that have properties, capacities or tendencies that exert themselves at specific physical circumstances (Cartwright 1989). For example, a spring that has the *tendency* of going back to its original position, chemical substances that *tend* to react with other substances, hot and cold bodies that *tend* to respond to the temperature of their environment, magnets that have the *capacity* of causing a voltage, and peas that have the *property* of producing flowers of particular colours. These examples also illustrate that constructing the description of a physical phenomenon involves reference to observable or measurable physical occurrences such as the *change* of temperature, pressure or colour, the *disappearance* or *transformation* of substances, the *formation* of gas, the *production* of magnetism or electricity, and the *rotation* or *movement* of objects. Hence, 'describing' reproducible phenomena in terms of so-called phenomenological laws often involves the introduction of new *physical concepts* that denote specific physical properties such as 'elasticity', 'diffusivity', 'electrical resistance' and 'refractivity', held responsible for the observed or measured capacities and tendencies.

Scientists in the mathematical tradition, on the other hand, are interested in the mathematical character of an occurrence (i.e., the patterns of measurable variables of a target system such as the planetary system). In constructing a mathematical phenomenon on the basis of measured data-sets (which are represented in, e.g., a table or graph), scientists 'observe' or 'discern' straight or parabolic lines, circles, ellipses, angles, sequences, ratios and all kinds of other regular mathematical patterns (e.g., represented in a mathematical formula or graph). In classical astronomy, for instance, scientists observed positions of the planets and constructed orbits in a geometrical space for describing them. In geometrical optics, scientists observed refraction and reflexion of light-rays at surfaces from which they constructed straight lines at certain angles on surfaces in a geometrical space. In harmonics, scientists observed regular movements like waves or oscillators, which they described by *mathematical concepts* such as frequencies, ratios, amplitudes and wavelengths. It appears from these examples that re-used or newly introduced mathematical concepts from mathematics, such as distance, angle, circle, ratio, and frequency are invoked when discerning a phenomenon from observations or measured sets of variables, which makes it a mathematically constructed phenomenon.

My presentation of these examples suggests that reproducible physically and mathematically constructed phenomena already are theoretical interpretations of 'raw' observations and measured variables, because the given phenomenological descriptions of them actually are causal laws or mathematical formulae, respectively. In other words, a reproducible phenomenon is a specific law-like behaviour, either physical or mathematical in character. This view on how scientists 'see' or 'discern' or 'construct' phenomena diverges from authors who are inclined to realist interpretations of phenomena such as Bogen and Woodward (1988).[9]

On this account of phenomena, the two traditions involve different metaphysical background pictures that guide what scientists recognize as significant kinds of phenomena. In the experimental tradition, scientists consider basic phenomena to be the law-like behaviour of physical objects (including natural interactions between them, and experimental or technological interventions with them). Conversely, in the mathematical tradition, naturally or experimentally produced data-sets and mathematical structures describing them are taken as basic. As said, a metaphysical background picture can be understood literally. Conversely, I promote to understand them as conceptual schemes necessary for structuring and interpreting the world. In the case of constructing descriptions of physical and mathematical phenomena, respectively, this means structuring and interpreting of 'raw' observations and measured data in terms of either physical objects and their properties, or mathematical structures.

According to Kuhn, in the first quarter of the nineteenth century, a number of experimental-Baconian fields became mathematized (Kuhn 1977: 61). In my account, incorporating mathematics occurs when simultaneously with the production and description of a physical phenomenon, a set of measured variables is produced (e.g., by the use of a variety of measurement instruments) and mathematically described. For instance, additional to finding a causal relation between the pressure and volume of a gas by a mere physical interaction with the device (e.g., by interventions with a gas-containing cylinder that is closed airtight with a movable piston), Boyle found a mathematical pattern in experimentally measured data sets of the volume and pressure at a constant temperature. The mathematical pattern tells that the value of the pressure is inversely proportional to the value of the volume (Boyle's law). In combustion experiments, Lavoisier measured gas-volumes and masses of chemical substances before and after burning. From this, he found reproducible ratios between the data. Next to his findings of physical phenomena (i.e., descriptions of qualitative changes of matter in burning), he thus constructed a mathematical phenomenon. Faraday, next to the physical phenomenon that a moving magnet produces electricity, found as a mathematical pattern that the resulting voltage is directly proportional to the speed of movement of the magnetic bar. Mendel, also next to the phenomenological description of hybridization experiments, found a mathematical pattern of ratios between the number of white and purple flowers in these experiments.

Hence, an experimental approach can become mathematized by the simultaneous production of measured data and constructing a mathematical description of them, which I summarize as 'producing a mathematical phenomenon'. Since these examples also illustrate that experimental techniques are used for *generating* patterns of measurable physical variables, the mathematical approach has become 'experimentalized' as well. Importantly, the generation of mathematical phenomena in experiments is dependent on what can be measured, that is, of the instruments researchers have at their disposal. At the same time, not everything that can be measured is actually being measured in experiments. The significance of this situation is that different mathematical patterns can be produced from one target system (also see McAllister 1997), which implies that both physically and mathematically constructed phenomena involve a degree of arbitrariness.

The simultaneous production of physical and mathematical phenomena (and their phenomenological descriptions) in an experiment seems to suggest that experimental and mathematical approaches have merged and that the physical and mathematical phenomena actually coincide. This idea is wrong. This is firstly, because the same experiment (or target system) can produce different physical phenomena depending on how scientists perform the experiment and how they construct descriptions of the phenomena. The same holds for simultaneously produced mathematical patterns, which result from more or less arbitrary combinations of measurable parameters. Secondly this idea is flawed, because it suggests that there is no fundamental difference between constructing physical (e.g., causal) and mathematical description of the behaviour of the target systems. On the contrary, the crucial thing that has been gained by 'mathematization' and 'experimentalization' of the two approaches, respectively, is that the resulting integrated approach of producing different kinds of phenomena enables scientists to *relate* the two distinct ways of describing the behaviour of a target system. The importance of recognizing that we still have to deal with two different kinds of phenomena, which are held together by the target system that generated them, is that physically and mathematically constructed phenomena have distinctive roles. These roles are both in the construction of theoretical interpretations, and in testing whether they meet epistemic criteria such as adequacy, simplicity, and coherence with well-accepted knowledge.

Jim Bogen and Jim Woodward (1988) introduced the necessity of talk about phenomena next to data, in order to account for how scientific practices produce theories. As suggested above, I propose to add an additional element to their taxonomy: the target system. Furthermore, unlike the relationships Bogen and Woodward proposed between data, phenomena and theories, I suggest that scientists go back and forth between them. To do so involves: (i) constructing (an experimental model of) the target system with which they perform experiments, (ii) producing 'raw' observations and data-sets by interventions with it, (iii) constructing descriptions of physical and mathematical phenomena, i.e., physically and mathematically formulated phenomenological laws, and (iv) constructing theoretical interpretations of these different kinds of phenomena.

Significant distinctions of the two traditional approaches continue to exist, not only because the one focuses on 'physical phenomena' whereas the other focuses on 'mathematical phenomena', but also because they produce fundamentally distinct kinds of explanations of the respective phenomena. Theoretical interpretations of the first type of phenomena usually are in terms of theoretical entities and their properties, capacities or tendencies, whereas scientists aim to interpret the other type of phenomena in terms of fundamental axiomatic systems. The latter phase of constructing theoretical interpretations of phenomena in terms of causal-mechanistic and/or mathematical models may either be guided by only one kind of reasoning, or by integrated causal-mechanistic and mathematical reasoning respectively. In this latter case, a scientific practice has developed the skill of productively utilizing the two approaches in a mutual interaction.

As suggested, physically and mathematically constructed phenomena ask for different kinds of theoretical interpretations. According to Kuhn, explanations in the experimental tradition are in terms of corpuscular-mechanical ideas. Although experimental traditions have become mathematized, when reasoning within the disciplinary matrix of what I will now call a causal-mechanistic style, this style entails a metaphysical background idea that guides and enables the construction of scientific explanations of phenomena in terms of (postulated) unobservable objects or 'theoretical entities'. Theoretical entities are physical objects that carry stable properties, capacities or tendencies. The entities, nor their properties, capacities or tendencies can be observed directly. At the same time, they are held responsible for bringing about the observed phenomena through their causal-mechanistic workings or by instrumental interactions with them. Atoms and molecules, for instance, have certain properties (like mass, size, velocity and energy) and tendencies (such as the tendency to react in particular ways with specific atoms or molecules at specific physical conditions, like temperature, pressure or chemical potential). They have been postulated for explaining observed phenomena in chemistry. Caloric particles having the tendency to flow from objects at high temperatures to objects at low temperatures, have been put forward for explaining observed phenomena in the science of heat. Heavy bodies having the capacity to interact with other heavy bodies by means of gravitational forces have been used for explaining phenomena in mechanics. Electromagnetic fields that exert forces on electricity or magnetism carrying objects have been suggested for explaining phenomena in electricity and magnetism. Genes – i.e., stable carriers of genetic factors that are transported from parents to offspring – have been used to explain the inheritance of traits in biology. Finally, elementary particles with properties such as mass, energy, electrical charge, momentum and spin, have been postulated in particle physics for explaining the character of fundamental building blocks of the universe.

An important aspect of the way in which 'capacity carrying theoretical entities' postulated in explanations of phenomena are construed is that scientists aim to conceive of something (the object and/or its properties) with which they can intervene in experiments by means of instruments. Therefore, in experimental approaches, successful intervention by means of experiments and instruments is important to the justification of theoretical entities as proper explanations of phenomena. This is in addition to epistemological criteria, such as logical consistency, coherence with accepted scientific knowledge and theories, simplicity, intelligibility, and predictive power. Authors such as Hacking (1983) and Nancy Cartwright (1989) take the possibility of experimental intervention as the most important for believing that theoretical entities (Hacking) and the tendencies and capacities (Cartwright) postulated in scientific theories really exist, yet, at the cost of the truth of mathematically formulated laws. As an alternative to their idea that we are obliged to choose between these options, I propose to regard explanations in terms of theoretical entities versus explanations in terms of fundamental laws of physics as distinct kinds of theoretical interpretations of two kinds of phenomena, which enable various kinds of epistemic enterprises held together by the target system.

How then should we understand theoretical interpretations in terms of mathematical laws? Kuhn claims that classical mathematical sciences drew axioms, concepts, and technical vocabulary from geometry (Kuhn 1977: 37). Hence, in classical sciences, geometry was sufficient as a mathematical framework within which the laws of classical physical sciences could be constructed. Following up on this idea, the use of mathematics in constructing, and fundamental laws in interpreting mathematical phenomena is very similar to how Euclidian axioms are used in constructing and interpreting geometrical structures – that is, similar to how geometrical structures are deduced from Euclidean axioms in geometry, observed patterns and structures of measured quantities are deduced from fundamental laws of physics (Boon 2009).

In modern physics, geometry is no longer sufficient. Scientists such as Newton, Maxwell, Boltzmann, Schrodinger, and many others, needed to postulate new mathematical concepts and techniques that allow for constructing fundamental laws from which measured data patterns could be deduced. In this way, new mathematical frameworks were constructed within which scientists could mathematically model the observed patterns and structures of data produced by specific kinds of target systems. Newton, for instance, invented fundamental laws of motion, for which he used mathematical concepts such as vectors – which mathematically describe quantities that have both magnitude and direction – for describing velocity, momentum, acceleration and force. This new mathematical framework allowed for a mathematical definition of force as presented in Newton’s first and second law of motion.

This account implies that Newton’s first two laws of motion can be understood as *mathematical* axioms from which patterns of moving bodies in space can be mathematically deduced.[10] The latter point is important, since understanding Newton’s notion of force as a mathematical concept avoids the need of a physical explanation of force, e.g., in terms of corpuscular-mechanistic ideas or causal-mechanistic workings of masses.

Similarly, Maxwell employed and invented mathematical concepts and techniques such as field-lines, potential, flux, gradient, vector, divergence, and circulation (Verschuur

1993, Simpson 1998). These concepts and techniques allowed him to construct his fundamental laws of electricity and magnetism in such a way that relevant phenomenological laws (i.e., mathematical descriptions of sets of measured variables), such as Ampere's law and Faraday's law, could be subsumed in a broader mathematical framework of fundamental laws. As a result, Maxwell also invented a new mathematical framework (i.e., his fundamental equations of electricity and magnetism, together with new mathematical concepts and techniques) from which the observed patterns in electricity and magnetism (described as mathematical laws) could be derived. Similar to Newton, Maxwell circumvented the need of a physical explanation of electricity and magnetism in terms of theoretical entities such as ether and ether-wind.[11]

6. Two styles of scientific reasoning

With the philosophical interpretation of well-known historical examples in the former section, I have illustrated that experimental and mathematical approaches of classical traditions have indeed been merged in the sense that physically and mathematically constructed phenomena of specific types of target systems can be produced simultaneously. Nevertheless, they still must be regarded as two different kinds of phenomena, held together by the target system. Belonging to the same target system ensures that they can be related to each other, but they cannot be reduced to each other.

This account is grounded in my view that the discernment of phenomena is already a theoretical interpretation of the behaviour of a target system. Discerning a phenomenon means producing a law-like physical and/or mathematical description of observations (including the results of physical interventions) and/or measured data-sets. How phenomena are understood and differentiated depends on the style(s) of scientific reasoning adopted in a practice. This view disagrees with interpretations of phenomena that consider them as independently existing entities. An unproductive consequence of upholding such a view is that different types of descriptions of phenomena must be essentially the same, which implies that they must be reducible to each other.

Hence, my view proposes that, on the one hand, different kinds of descriptions are about the same target system, but on the other hand, they describe different kinds of phenomena. These different kinds of descriptions can be related but not reduced to each other. Additionally, the presented historical examples illustrate that phenomena are traditionally/historically explained in two different ways. Physically constructed phenomena are explained in terms of physical entities, properties, capacities, etc., thus producing causal laws and/or causal-mechanistic models. Mathematically constructed phenomena, in contrast, are explained in terms of mathematically formulated axiomatic systems (often called, abstract fundamental theories), thus producing mathematical laws and/or mathematical models as theoretical interpretations of the phenomenon. Successful scientific practices, such as biotechnology and nanotechnology, are considered as such when they are able to employ the two approaches in a mutual interaction.

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Notes

[1] The difference between Lynch's (1998) and Cartwright's (1999) metaphysical pluralism is that Lynch's pluralism is about our ways of conceptualizing, whereas Cartwright assumes that this plurality exists in the world, independent of us. Lynch's position is highly influenced by Kant's transcendental idealism (which is why he refers to his position as a relativistic Kantianism) and Putnam's (1981) internal realism.

[2] Elsewhere, I follow Kant in arguing that metaphysical background ideas are indispensible in doing science, but must be understood as regulative ideas that guide our epistemic activities, rather than claims about how the world really is independent of us (Boon forthcoming b, also see Neiman 1996 and Chang 2009).

[3] My view on phenomena differs from Bogen and Woodward (1988). With regard to the relation between phenomena and patterns of measured data, they propose that data play the role of evidence for the existence of phenomena. Moreover, data for the most part can be straightforwardly observed, whereas phenomena cannot. They defend that theories predict phenomena, whereas data typically cannot be predicted or systematically explained by theory. I agree that data can function as evidence for phenomena (although I disagree with their ontological interpretation of phenomena as pre-given independent entities 'out there'). I also agree that theories (or scientific models) predict phenomena rather than data as the latter are idiosyncratic to an experimental set-up. However, I dispute that patterns of measured variables cannot be predicted or explained by scientific models. Moreover, although data are 'straightforwardly observed', patterns of measured variables are not. Finally, patterns of measured variables, do not somehow coincide with, or represent the physical phenomenon. For these reasons, I will also call the data-pattern a phenomenon.

[4] My position deviates from Giere's (2006) scientific perspectivism in the following sense. Giere assumes that different (instrumental and theoretical) perspectives coincide when it comes to the structure of the real objects. In contrasts, my position is that we are intellectually capable of different ways of conceptually interpreting and structuring of what we observe or measure (Boon 2009); distinct epistemic outcomes (such as laws and models) are held together by the real target system, which explains how it is possible that we are capable of relating them in our further epistemic activities.

[5] Salmon's two examples and their scientific explanations are summarized as follows: (1) A balloon filled with helium will move forward in an airplane that accelerates rapidly for takeoff because: (a) the sum of forces exerted on it will push it to the front, which is a causal explanation, or (b) according to Einstein's principle, acceleration is physically equivalent to a gravitational field, which is a fundamental or unification-type explanation. (2) The carriage with no brakes on the wheels and which holds an actively pushing, pulling, rocking and bouncing baby, will not move away from its horizontal position on the floor because: (a) all of the forces exerted by the baby on the carriage, and the carriage on the baby, are cancelled out, which is a causal explanation, or (b) according to the law of conservation of linear momentum the system of the baby and the carriage is essentially isolated when the brake is off, which is an explanation in the unification sense for it appeals directly to a fundamental law of nature.

[6] Hacking (1983) articulated this distinction by distinguishing between realism about entities versus realism about laws. By arguing in favour of entity-realism, and rejecting realism about laws, he exemplifies that adopting both is philosophically problematic. In current debate, the difficulty of accepting incompatible metaphysical ideas is illustrated in the controversy between realism about theoretical entities (Hacking 1983) and their capacities (Cartwright 1989) versus realism about abstract structures in the world, such as Worrall's (1989) structural realism. These competing versions of scientific realism seem to reflect the distinct metaphysical ideas of the two kinds of scientific approaches (experimental and mathematical) and the character of their typical epistemic results (e.g., causal-mechanistic and mathematical models) in current scientific practices. According to Worrall (1989), we should not accept standard scientific realism, which asserts that the nature of the unobservable objects that cause the phenomena we observe is correctly described by our best theories. However, neither should we be antirealists about science. Rather, we should adopt structural realism and epistemically commit ourselves only to the mathematical or structural content of our theories. Clarifying surveys of the debate on structural realism have been presented by Psillos (2000) and Ladyman (2008).

[7] Hacking (1992: 56-57) defends that coherence of elements that together constitute a laboratory science (namely, 'ideas', 'things' and 'marks') explains its stability. This idea can be understood as adding materiality to Kuhn's idea of disciplinary matrix, thus expanding on Kuhn's notion of 'coherency within a disciplinary matrix'. I fully agree that instruments and experiments also must be 'matched-in'. However, I disagree to the suggestion that a laboratory science is one self-vindicated whole. Conversely, I defend that a scientific practice may incorporate incompatible descriptions of phenomena, laws, models and theories, which are coherently constructed within the confines of a specific disciplinary matrix (or, style of reasoning and conceptual scheme), and which may function complementary within one practice. This account explains better than Hacking's, how it is possible that practices evolve due to vivid exchange with other practices, such as in the case of biotechnology and nanotechnology.

[8] In this article, I utilize two accounts of causal interaction: (1) Woodward's (2003) manipulationist account of causal interaction which accounts for the cause-effect relationship that (may) result from interventions (e.g., in experiments), and (2) Cartwright's (1989) notion of capacities and tendencies, which are properties – however, not the 'essential' or 'primary' properties that characterize a specific type of object, but properties that (only)

exert themselves at specific physical conditions. An example is oxygen, which has the capacity of oxidizing iron. This capacity only manifests itself at a sufficiently high temperature, etc. Another example is gold, which has the capacity of being red. This capacity only manifests itself in nano-sized gold particles, etc.

[9] The debate on phenomena and data between Bogen and Woodward (1988), McAllister (1997) and Glymour (2000) considers whether the distinction between phenomena and patterns of data proposed by B&W can be maintained while at the same time holding on to the idea that descriptions of phenomena do not involve theoretical interpretation (phenomena as mini-theories). McAllister denies that this view can be coherently defended, while Glymour denies that phenomena add anything to data. I agree with Bogen and Woodward that a distinction between (in my terms) patterns of measured variables and phenomena is important. At the same time, I deny their ontological interpretation and argue that phenomenological descriptions of physical and mathematical phenomena involve 'non-trivial' theoretical interpretations (See also note 3 above).

[10] This so-called positivistic interpretation of Newton, according to which Newton's introduction of the notion of force primarily was a mathematically defined concept rather than a physical concept, has been abandoned by most historians of science (personal communication with Steffen Ducheyne, also see, Janiak 2007, Ducheyne 2007). Nevertheless, my interpretation of Newton's abstract fundamental theory as a mathematical framework within which mathematically constructed phenomena of specific types of target systems (e.g., Newtonian systems, also see Giere 1988, 2006) can be interpreted, is a philosophical view rather than a historical claim about what Newton actually believed. In other words, my philosophical point (which will be explained in more depth elsewhere) is that Newton's theory of motion can be understood as an abstract mathematical theory that enables us to account for mathematical patterns of observed or measured data produced by target systems of a specific type, similar to how Euclidean geometry is employed in discerning and accounting for geometrically constructed phenomena. Subsequently, a physical interpretation of 'force' enables to relate this mathematical approach with physical, causal-mechanistic approaches.

[11] Again, this is not a historical claim. The philosophical crux is that mathematical ways of thinking about a target system can in principle occur independently from physical ways of thinking about it. In that case, thinking about the target system abstracts from physical interpretations; it is conceptually understood as a mathematical system.