This article is a draft. It has been presented at the second biennial SPSP conference 2009, Minneapolis, Minnesota. Please do not quote, cite, or distribute without the agreement of the authors. September 16, 2009.

How do models give us knowledge? The case of Carnot's ideal heat engine

TARJA KNUUTTILA AND MIEKE BOON

Department of Philosophy, University of Helsinki, Helsinki, Finland

Department of Philosophy, University of Twente, Enschede, The Netherlands

Abstract:

Our concern is in explaining how and why models give us useful knowledge. We argue that if we are to understand *how models function in the actual scientific practice* the representational approach to models proves either misleading or too minimal. We propose turning from the representational approach to the artefactual, which implies also a new unit of analysis: the activity of modelling. Modelling, we suggest, could be approached as a specific practice in which concrete artefacts, i.e., models, are constructed with the help of specific representational means and used in various ways, for example, for the purposes of scientific reasoning, theory construction and design of experiments and other artefacts. Furthermore, in this activity of modelling the model construction is intertwined with the construction of new phenomena, theoretical principles and new scientific concepts. We will illustrate these claims by studying the construction of the ideal heat engine by Sadi Carnot.

1. Introduction

If there is any theme that unites philosophers as regards models it is that of representation. Models are generally presumed to be representations. While scientific models as specifically designed artefacts certainly belong to a class of public objects called representations, something more is implied by the idea of representation in the context of modelling. Namely, the claim that models are representations plays out their relational nature. Models are thought of as being inherently *models of* something and, more often than not, this something is understood in terms of some real objects, processes, or more generally, some natural "phenomena". Thus we take it to be commonly accepted in the philosophy of science that scientific models represent some real target phenomena – or target systems.

This seeming agreement disguises the fact that different philosophers understand representation in vastly different ways, yet at the bottom of this consent seems to be the belief that models give us knowledge in virtue of representing (some selected aspects) of external world sufficiently accurately (Bailer-Jones 2003; da Costa and French 2000; French and Ladyman 1999; Frigg 2002; Morrison and Morgan 1999; Suárez 1999; Giere 2004). The representational conception of knowledge as that of accurate representation which underlies this belief has long roots in Western culture, a huge topic we cannot even hope to cover in this paper. However, we argue that if we are interested in *how models give us knowledge in the actual scientific practice* the representational approach to models proves too minimal. Although we do not want to dispute the fact that models often are used to represent some real target systems, we claim that the representational approach to models is rather geared towards the question of justification, and does not provide us resources to tackle their function in knowledge-acquisition.

To offer an alternative way of approaching models, better suited to tackle the question concerning the epistemic productivity of models, we approach models as epistemic tools. Thus the "as… " locution serves here to point out that we are not primarily interested in defining what models are, or are not. Approaching models "as" epistemic tools we rather wish to invoke the dimension of use. As from our pragmatist perspective, we take it that alike scientific models also philosophical accounts are constructed for certain purposes. Accordingly, conceiving models as epistemic tools proves to be an useful tool itself, for the philosophical purpose of finding out how models and modelling gives us knowledge. Also, we would wish to guard our argument against such reading which takes us to claim that models are not representations. Rather, we suggest that scientific models could be usefully approached through their artefactual dimension as constructed entities that give theoretical interpretations of target phenomena in view of particular epistemic purposes.

Our suggested turn from the representational approach to the artefactual implies also a new unit of analysis: the activity of modelling. Modelling, we suggest, could be seen as a specific practice in which concrete artefacts, i.e., models, are constructed with the help of specific representational means and used in various ways, for example, for the purposes of scientific reasoning, theory construction and design of experiments and other artefacts. Furthermore, in this activity of modelling the model construction is intertwined with the construction of new phenomena, theoretical principles and new scientific concepts. In this way the justification of a model is partly built into it in the process of modelling, implying that the representational approach, albeit its focus on justification, misses a lot of how models are justified in scientific practice.

To give a flavour of scientific practice and a practical example of how our account of models as epistemic tools enhances our understanding of modelling, we study the construction of the Carnot model of a heat engine, which is a classical example of a technological device that was subject to scientific modelling. Although our account of Carnot's modelling is based on Carnot's writings, we do not present it as an accurate historical description of how Carnot actually went on in his modelling task but wish to remind our readers of its being inevitably a philosophical reconstruction. What is more, Carnot himself did not call his theoretical account of the heat-engine a model. The notion of a scientific model in its present sense was not in use those days [cf. Bailer-Jones, 1999]. Thus it is only with the benefit of hindsight that the scientific community calls it a model of the heat-engine.

Our choice of the Carnot model is in part due to its familiarity, historical import and simplicity, but in part we have selected it for strategic reasons. Often the real target systems that models are supposed to represent are not known by us, but in the case of a heat engine a definite real target system exists. Furthermore, since it is a thing constructed by us, we should be able to assess in which sense, if at all, the Carnot model of a heat engine can be considered an accurate, although selective, representation of the real heat engine. A possible objection to this case might be that being an engineering model the Carnot model has not the same status as scientific models in theoretical sciences proper. We think that such an objection is not valid for the reason that engineering sciences should not be confused with engineering. Whereas the former concerns scientific research in the context of technological applications, the latter is engaged in concrete design and development. In fact, engineering sciences make a good place to study modelling as they characteristically strive by using theoretical models to explain, predict or optimize the behaviour of devices, processes, or the properties of diverse materials, whether actual or possible.

2. Models as Representations

As we have already pointed out, according to received wisdom models give us knowledge because they represent their supposed external target objects more or less accurately, in relevant respects and sufficient degrees. This kind of formulation already suggests that there is a special sort of relationship between a model and its target which is most commonly analysed in terms of similarity or isomorphism. A well known metaphor of how models represent their target objects and give us useful knowledge of it, is Giere's metaphor of maps (such as geographical maps of the Swiss Alps, a map of high-ways in Europe, or the map of the underground system in London). These maps give us useful knowledge about, for instance, how to travel from A to B, because a map represents certain selected aspects of a specific system in the real world. As we will explain somewhat further below, we do not favour maps as metaphors of models. Nevertheless, this example serves to show the fundamental differences between the different ways representation has been analysed by the philosophers of science. Namely, there runs a dividing line separating those accounts that take representation to be a two-place relation between a model and its target system, from those which argue that also the representation-users and their purposes should be taken into account. According to the latter, representation is irreducibly a pragmatic notion. What this means as regards the map example is that the two-place accounts focus on the morphic or other resemblances between the map and its target system, whereas pragmatic accounts take as their starting point the fact that there is no single determinable way in which any target can be mapped. Maps are made in order to convey information for their users and thus they depict their targets according to the purposes of the users. What is more, the user needs to be able to locate oneself in the map, for the map to be useful at all.[i]

The conviction that representation can be accounted for by reverting solely to the properties of the model and its target system is part and parcel of the semantic approach to scientific modelling. According to the semantic conception, models specify structures that are posited as possible representations of either the observable phenomena or, even more ambitiously, the underlying structures of real target systems. The representational relationship between models and their target systems is analysed in terms of isomorphism: a given structure represents its target system if both are structurally isomorphic or partially isomorphic to each other. Isomorphism refers to a kind of mapping that can be established between the two that preserves the relations among elements. Consequently, the representational power of a structure derives from its being isomorphic with respect to some real system or a part of it (van Fraassen 1980, 45, 64; Suppe 1974, 97,92; French and Ladyman 1999; da Costa and French 2000; French 2003). Other candidates offered for the analysis of representation by the proponents of the semantic view are similarity (Giere 1988) and homomorphism (Bartels 2006, Ambrosio 2007). However, differing from the former mentioned semantic view philosophers, neither Giere (see e.g. Giere 2004, 2006) nor Bartels or Ambrosio try to base representation solely on the two-place relationship between the model and a target.

The semantic conception of models as a putative analysis of representation gives rise to persistent philosophical problems. Firstly, isomorphism is a relationship between two structures, whereas scientific representation assumes a relationship between a model structure (in case we are prepared to reduce models to structures) and a real world target system. Mere structural isomorphism is not sufficient for representation since the same structure can be instantiated by different systems and thus isomorphism alone is thus not able to fix the extension of representation. On the other hand, a certain target system need not have an unique structure; depending on the perspective adopted, it can be sliced up differently. (See Frigg 2006, 56-59). Secondly, the parts of the real world we aim to represent are not "structures" in any obvious way. It is possible to ascribe structures to some parts of the real world, but this involves that these parts of the empirical world are already modelled (or represented) somehow. Thus the isomorphism required by the semantic account actually concerns the relationship between a theoretical model and a data model, rather than model and the real world (see Suppes 1961). Thirdly, the critics of the semantic account of representation have pointed out that as an analysis of representation isomorphism has wrong formal properties. For instance, isomorphism denotes a symmetric relation whereas representation does not: we usually want a model to represent its target system but not vice versa.[ii] Fourthly, from the scientific practice point of view, the idea that representation is either a structurally accurate depiction of its object or not a representation at all does not fit our actual representational practices. It is characteristic of scientific models that they are inaccurate in many ways (all of which cannot be accounted for by introducing the idea of partial isomorphism). Indeed, the important role of idealizations, simplifications, approximations and tractability considerations in modelling are more often than not neglected by the semantic perspective.

The pragmatic approaches, in turn, make representation less a feature of models and their target systems than an accomplishment of the representation users (Suárez 2004, Giere 2004, Bailer-Jones 2003, Frigg 2006). These studies criticize the assumption that representation could be regarded as a two-place relationship of correspondence between the representative vehicle and its target. This way of conceiving representation, attempts, as Suárez (2004) has aptly put it, "to reduce the essentially intentional judgments of representation-users to facts about the source and target objects or systems and their properties" (p. 768). In contrast, the pragmatic approaches point out that no one thing is a representation of something else in and of itself; it has to be always used by the scientists to represent some other thing (Teller 2001, Giere 2004). Consequently, what is common to pragmatic approaches is their focus on the intentional activity of scientists as representers, and the denial that the relationship of representation to what is represented can be based only on the respective properties of the representative vehicle and its target object.

As pragmatic approaches ground representation on the specific purposes and representing activity of humans, nothing very substantive can be said about the relationship of representation in general. This has also been explicitly admitted by the proponents of the pragmatic approach (see Giere 2004, Suárez 2004), of whom Suárez has gone farthest in arguing for a minimalist inferential account of representation which resists saying anything substantive about the supposed basis on which the representational power of representative vehicles rests, i.e. whether it rests, for instance, on isomorphism, similarity or denotation. According to Suárez, such accounts of representation err in trying to "seek for some deeper constituent relation between the source and the target", which could then explain as a by-product why, firstly, the source is capable of leading a competent user to a consideration of a target, and secondly, why scientific representation is able to sustain "surrogate reasoning".

What has so far escaped notice in the discussion on scientific representation is that the pragmatic approach to representation has, in its minimalist guise, rather radical consequences for how we conceive of models. Namely, if we accept the minimalist approach to representation, not much is established in claiming that models give us knowledge *because* they represent their target objects. Thus while it may be the case that the pragmatist account offers most that can be said about representation at a general level, it makes the representational approach hopelessly minimal as an explanation of how we can gain knowledge through models.

Alternatively, to give more content to the notion of representation, several pragmatically inclined philosophers have used the notion of resemblance or similitude (see e.g. Giere 1988, 2004, Godfrey-Smith 2006, Weisberg 2007). Indeed, if it is a case that many if not most things can be taken to be similar to most other things, then it is we who pick the "appropriate similarities" – and in this sense the assimilation of a similarity account of representation to a pragmatist account seems an entirely appropriate step to take. However, even in this case the representational relationship is considered to be irreducibly intentional, and the addition concerning *perceived* similarities does not, in our view, make the pragmatic account any more informative as to how models give us knowledge.

In sum, as regards scientific representation we face the following dilemma. Either we offer it a strong account in terms of the properties of the model and its target, which is what the semantic conception of representation aims at but fails for the reasons mentioned above, or then we settle with the pragmatist minimalist accounts, which stop short of being informative as to the epistemic value of models. Moreover, in their focus on representational relation of a ready-made model and its putative target system neither of these accounts seem very fruitful in understanding how models give us knowledge. They fail to see, that to a significant extent, models are justified through their construction, and what is more, give us knowledge by how they are constructed. Rather than being straightforward representations of some already known physical or otherwise real phenomena, models often depict some tentative mechanisms, processes or solutions that serve as a basis for various inferences, interventions and experimental set-ups. On many occasions, scientific models are used primarily as demonstrations, exemplifications, proofs of existence, etc. Thus they function rather as multipurpose tools than as straightforward representations of real target systems. Our account of models as epistemic artefacts pays attention exactly to this multiplexity of models (cf. Merz 1999).

3. Models as Epistemic Artefacts

Although often used and intuitively appealing, the map-example may actually lead us astray when it comes to the epistemic value of models. It makes it easy to hold both the pragmatist position and a structural resemblance view of representation, since it suggests that models can be used to help us orienting in the world because they resemble real target systems. While this certainly applies to maps, there are good reasons to question whether a map can provide a good metaphor for scientific models. Why should this be so? The map metaphor suggests that there could be a direct representational relationship between the model and a target. We can more or less directly observe the properties of the terrain, e.g. high-ways or hills, and measure and render them in a convenient form in the map. But this not how scientific models are usually constructed, since it is characteristic of scientific modelling that it involves such epistemic activities as discerning specific types of phenomena, conceptualizing 'non-directly observable' objects, properties, or processes, and bringing phenomena under specific types of 'non-empirical' theoretical principles or concepts.

This indirectness of models as regards to real world systems has recently been taken by Michael Weisberg (2007) and Peter Godfrey-Smith (2006) as the distinctive characteristic of modelling. According to Weisberg and Godfrey-Smith, modelling can be viewed as a specific theoretical practice of its own that can be characterized through the procedures of indirect representation and analysis that modellers use to study the real-world phenomena. With indirect representation they refer to the way modellers, instead of striving to represent some real target systems directly, rather construct simple, ideal model systems to which only a few properties are attributed. They argue that in modelling, models come first in the sense that they are constructed and analysed before the relationship between the model and any target system is assessed, “if such an assessment is necessary” (Weisberg 2007, 209). Thus modellers may go on studying the model systems created without too much explicit attention to their relationship with the world, which makes models independent from any real target systems.

But how, then, are models as independent objects able to give us knowledge? Whereas Godfrey-Smith evokes the “*effortless* informal facility” with which we can assess similarities between imagined and real-world systems, Weisberg refers to the notion of representation. But reverting to representation, not to mention mere similarity, would take us back to the problems discussed above. In contrast, what we find the most important point in viewing models as independent things is that it enables us to appreciate their functional characteristics, that is, the different purposes for which they are used in scientific practice. This gives us, we suggest, a clue to how to appreciate the epistemic properties of models from another perspective than that provided by representation.

In stressing the importance of the functional characteristics of models for their epistemic value, we follow Morrison and Morgan (1999) who point out that we learn from models by constructing and manipulating them. Also Morrison and Morgan consider models as independent entities, although on their construal models gain their (partial) independence from theory or data rather than from real targets. This is because, besides being composed of both theory and data, models typically also involve “additional ‘outside’ elements” (1999, 11). Boumans (1999) in turn goes on to disentangle models from the theory-data framework altogether. In his view models are independent things constructed from as heterogeneous “ingredients” as analogies, metaphors, theoretical notions, mathematical concepts, mathematical techniques, stylised facts, empirical data and even relevant policy views. In consequence, part of the justification of a model is built into it through the initial justification of the ingredients that are “baked” into a model.

Taken together, the aforementioned approaches suggest that models should be addressed as independent things with some initial built-in justification and from which we learn by manipulating them. Building on this approach, we wish to go even one step further: We suggest conceiving of models as *concrete objects*, constructed for certain *epistemic aims* making use of various representational means and whose cognitive value derives largely from our *interaction* with them (Knuuttila 2008, Knuuttila and Merz, 2009). Consequently, scientific models can be considered as multifunctional *epistemic artefacts* (Knuuttila 2005, Knuuttila and Voutilainen 2003). The point of stressing the concrete artefactual nature of models follows from our focus on the epistemic functioning of models. That is to say, if our aim is to understand how models enable us to learn from the processes of constructing and manipulating them, it is not sufficient that they are considered as independent; they also need to be concrete in the sense that they must have a tangible dimension that can be worked on. This concreteness is provided by the material embodiment of a model: the concrete representational means through which a model is achieved gives it the spatial and temporal cohesion that enables its manipulability. This also applies to so-called abstract models: when working with them we typically construct and manipulate external representational means such as diagrams or equations.

Our suggestion of approaching models as *epistemic artefacts* involves several largely novel features: Firstly, it conceives of models as a concrete constructed objects, which are expressed by external representational means and whose construction both “affords and constrains” scientific reasoning. Part of this affording and constraining nature of models is due to the representational means used.[iii] For instance, pictures or graphs both “afford” different kinds of reasoning than linguistics expressions or mathematical equations. The other part of the affording and constraining nature of models can be attributed to the idealizations, abstractions and approximations made. Modellers seek to develop their models in such a way that it renders their initial problem more accessible and workable helping them to tackle it in a more systematic manner. Thus from our perspective, models provide by their construction external aids for our thinking, something that cognitive scientists have approached in terms of the notion of *scaffolding*. According to them external representational scaffolding both narrow the space of information search by localizing the most important features of the object in a perceptually salient and manipulable form, and enable further inferences by making the previously obscure or scattered information available in a systematic fashion (see e.g. Larkin and Simon 1989, Clark 1997, Zhang 1997).

Secondly, our approach puts to the fore the *evolving* nature of model building: Models are typically constructed step-by-step which follows from considering models as concrete artefacts, the epistemic value of which follows from our interaction with them. We do not contend that models boil down to their concrete embodiment in some representational media, neither that their epistemic value follows from it alone. Rather, we suggest that the concrete embodiment of a model (whether symbolically or iconically rendered), draws together and integrates, in each stage of its development, the various empirical, theoretical and conceptual dimensions of its construction. In fact, as we will show in the case of the Carnot model, modelling typically involves a theoretical (re)description of the target *phenomenon* as well as the development of *theoretical principles* and *scientific concepts*. As the concrete model functions as an integrating tool as well as a scaffold for further scientific reasoning, it functions also as a tool of its own development.

Thirdly, our artefactual approach pays attention to two aspects of the *toolness* of models. On the one hand it pays attention to the diverse tasks of models in science such as prediction, design of experiments and theory development. On the other hand we wish to align our account with those developments in the philosophy of mind and language that try to seek alternatives for representationalism. Typically those accounts refer to the notion of a tool in order to avoid understanding mental content or linguistic meaning in terms of representation. In a similar vein we wish to attribute the epistemic value of models to their functional characteristics rather than to their representational nature. For instance, in the engineering sciences models are developed for the purposes of producing, controlling, or preventing some properties of materials or behaviour of processes and devices. Scientist in the engineering sciences build models for the purposes of imagining and reasoning about how to improve the performance of the devices, processes or materials of interest. These models involve imaginable properties and processes, and they incorporate measurable physical variables and parameters (e.g., in the case of chemical engineering, chemical concentrations, flow rates, temperature, and properties of materials such as diffusion, viscosity, density).

Fourthly, if models are not considered first and foremost as representations, what are, then, their targets? From our perspective, models are purposefully crafted devices the aim of which is to provide answers to some pertinent scientific problems. Thus the starting point of modelling in scientific practice is the question to be answered rather than the attempt to represent a certain real target system as accurately as possible.[iv] In fact, to strive for an accurate representation is probably not the most feasible cognitive strategy for problem-solving. The proponent of the representational account might try to take this into account by arguing that the requirement of accurate representation applies only to the relevant aspects of real systems. Yet, from our perspective, this kind of reply amounts to putting the cart before the horse. Modelling is a way to inquire what is relevant for a certain problem, taking into account that a well-formulated question is already an epistemic achievement.

In the following section we will exemplify the aforementioned aspects of our conception of models as epistemic artefacts by studying the Carnot model of the heat-engine. We highlight the process of modelling paying attention to the to the aim of the model, the way the original problem motivating the model construction was translated into a phenomenon to be accounted for, and how the model in the course of its development became a tool of its own development.

4. The Case of the Carnot Model of a Heat-Engine[v]

As we have argued above, the representational approach cannot explain how models give us knowledge in any other way than invoking the representational relation between the model and a real target system. An important aim of our analysis of the development of the Carnot model is thus to illustrate how conceiving of models as epistemic tools makes it intelligible how models give us knowledge and how they are justified. The key to this question lies in the activity of modelling, through which scientists develop a model step-by-step, building in new aspects by which the content of the model becomes richer and more advanced. In each modelling step the constructed content functions as an epistemic tool that ‘affords and constrains’ the further development of the model and the accompanying theoretical principles and concepts.

Our reconstruction of Carnot's development of the model of heat engine is primarily based on the line of his argument presented in *Reflexions on the Motive Power of Fire and on Engines fitted to develop that Power* (Carnot 1986, [1824]). Importantly, the steps distinguished below do not necessarily present a sequential order – these different aspects are modelled in a mutual interaction. As for the generalizability of our case, we do not claim that all the following steps are always present in modelling, nor, that no other steps could be distinguished in this or other modelling examples.

As for the importance of the actual representational means used in constructing the model, Carnot cast his model in terms of discursive reasoning by making assumptions and formulating principles. He did not have at his disposal such representational means as the well-known P-V diagram that was invented by Benoît Paul Émile Clapeyron only ten years after Carnot published his *Reflextions*, which enabled their successors to draw new conclusions from the model. Nevertheless, we claim that in the modelling, the conceptions Carnot developed by means of linguistic formulations, enabled him to build the model step-by-step, where the concrete discursively expressed model indispensably functioned as an epistemic tool in its own making through the whole modelling process.

Step I. Articulating the epistemic aim

The engineering sciences usually start from questions related to practical problems and applications, for instance, from the problem of how the functioning of a device can be improved. The problem that the French physicist and engineer Sadi Carnot got interested in was how to improve the performance (or efficiency) of heat engines. In his *Reflexions*, he writes that, "The study of these engines is of the utmost interest [because] their importance is immense, and their use is increasing daily." (ibid p. 61). Carnot is not interested in the 'trial-and-error' approaches familiar to engineering of his days. Instead, he aims at a theoretical answer to a fundamental question about the performance of heat engines:

> The question whether the motive power of heat [i.e. the useful effect that an engine is capable of producing] is limited or whether it is boundless has been frequently discussed. Can we set a limit to the improvement of the heat-engine, a limit which, by the very nature of the things, cannot in any way be surpassed? Or conversely, is it possible for the process of improvement to go on indefinitely?"(ibid p. 63)

This fundamental question illustrates a kind of general *epistemic purpose* common to the engineering sciences, to wit, finding out the fundamental limit to the improvement of the desired (or, to the opposite, undesired) capacity of a technological artefact (e.g., materials, processes or devices performing a specific function) via theoretical understanding of the very nature of this capacity. For this purpose a model of an ideally functioning technological artefact is constructed, which affords and constrains scientific reasoning about possible (hypothetical) interventions with the real technological devices (e.g. the real heat engines). Consequently, the Carnot model can be conceived as an epistemic tool, for reasoning about why, on the one hand, certain losses cannot be avoided, or how on the other hand, one could aim to minimize these losses of the heat engine. One obvious consequence of this problem-oriented approach is that the aim of modelling is not primarily that of *representing* some real target-system accurately, but producing a hypothetical device that meets the specific epistemic aim. Although our account of models as epistemic artefacts may seem especially tailored for the engineering sciences, we suggest that scientific modelling in general aims at answering specific questions. As a consequence, when coming across a scientific model, probing the intended epistemic aim of the model usually appears as a more sophisticated scientific attitude for understanding it than inquiring what the model 'actually' represents.

The claim that scientific modelling is usually motivated by a specific epistemic aim, and that the model can thus be considered as an epistemic tool designed to meet this aim, asks for further explanation of how this is supposed to happen. Basically, we suggest, modelling is not at all geared towards representing accurately some real target-system. For instance, drawing and describing the mechanical working of an existing heat-engine (in engineering) can be considered as an example of the representing of a target system, but what Carnot established was something quite different. The characteristic step-by-step construction of a scientific *model* is not due to the attempt to represent step-by-step the different aspects of some real target system, but it rather reflects how the theoretical principles and theoretical conceptions develop as the model gets more sophisticated and how the model in each consecutive phase of its development acts also an epistemic tool in its own making.

Step II. Discerning the target phenomenon

The purpose of Carnot's model was to give theoretical understanding about natural or fundamental limits to the performance of heat-engines. In order to get an intellectual grip on the problem, the problem had to be conceptualized in such a way as to make it cognitively accessible. This often involves conceptualizing some phenomenon in a new not necessarily obvious manner.

How is the phenomenon then (re)conceptualized? Generally, developing a scientific model for a technological artefact such as the heat-engine, involves conceiving of its functioning in terms of particular physical phenomena that produce its proper or improper functioning. Carnot assumed that, "in order to grasp in a completely general way the principle governing the production of motion by heat, it is necessary to consider the problem independently of any mechanism or any particular working substance." (ibid. p. 64) Hence, Carnot conceived of the functioning of the heat-engine, not primarily in terms of its mechanical working, but as a device that produces *motion by heat*.[vi] Therefore, the target phenomenon to be modelled became "the production of motion by heat".

Step III. Scientific conception of the target phenomenon

We hold that developing a conception of the target phenomenon in order to make it scientifically accessible, is an integral part of modelling. The target phenomenon is not simply observed in a straightforward manner, but involves creative reasoning towards a reasonable and productive conception of the functioning of the target system. This idea about the construction of a target phenomenon deviates from the common sense conception of the role of physical phenomena in scientific practice, in which the phenomenon to be modelled is supposed to stand apart from the model. Contrary to the idea that physical phenomena, to a certain extent, lay waiting for the perceptive scientist who inventively picks it up for further examination through modelling and other means, we emphasize that the description of the target phenomenon is not 'ready-made'. In this we partly follow Massimi (2008) who has argued against the view that physical phenomena are "empirical manifestations of what is there". As an alternative, she defends the view that, "phenomena are conceptually determined appearances". Although we will not adopt Massimi's vocabulary of appearances versus phenomena, the point to be taken from her work is that a description of a scientifically accessible phenomenon is not a straightforward, 'conceptually bare' representation of what there is. Instead, it has built in it scientifically significant conceptual content. In other words, when scientists discern a phenomenon, they do this by bringing an 'obvious, conceptually bare' occurrence ('appearance') either under already existing scientific concepts, or, sometimes, under a newly invented scientific concept. An occurrence to which no scientifically significant conceptual content has been attributed, usually remains scientifically inaccessible, and is not even recognized as a phenomenon in need of scientific explanation. Hence, we introduce an analytical distinction between, on the one hand, the target phenomena understood as 'conceptually bare' empirical (experienced) knowledge of the phenomenon such as the functioning of the heat engine (that is, as a device that produces *motion by heat*), and, on the other hand, the target phenomenon described (i.e., understood) in terms of (new) scientific conceptions and which thus becomes scientifically accessible.

By this distinction, we can now analyze how Carnot developed a scientific conception of the target phenomenon. Most probably he indeed started from empirical (experienced) knowledge in order to describe heat engines as devices that produce power from heat as a target phenomenon. As this description is ‘conceptually bare’, something more is needed for making it scientifically accessible. How does Carnot arrive at something that is not a mere empirical description, but a scientifically accessible target phenomenon? Importantly, Carnot brings the target phenomenon under a new scientific conception of heat and of how heat produces power, that is, of how heat *causes* the production of motive power. How does this work?

Carnot’s scientific conception of heat and of how heat produces power, can be summarized as follows: Motive power is produced by *transfer* (i.e., by *transportation* rather than by *transformation*) of heat. What Carnot means is that no heat is consumed in a cycle of the heat engine (in which gas is heated, then expanded – producing motive power, cooled, compressed, and heated again). According to Carnot, the *quantity* of heat in this cycle remains the same. Consequently, heat is conceptualized as a conservative quantity. He calls it *caloric* and conceives of it as a kind of indestructible heat-stuff, a substance, like mass. But contrary to mass, Carnot conceives of caloric as a sort of weightless, invisible fluid. This fluid is imagined as spontaneously transferring from hotter to colder bodies. By this *transfer,* caloric produces motive power without being consumed. In this conception of how caloric produces motive power, Carnot uses an analogy of how a water-flow produces motive power – for instance, in water-wheels, where water flows from high to low levels producing motive-power (the turning of the wheel) without the water itself being consumed.[vii] In this way, Carnot has developed a scientific conception of the target phenomenon by bringing it under a conception of how caloric produces motive power, thus making it scientifically accessible.

Accordingly, Carnot proceeds in modelling the heat-engine by conceiving of the target phenomenon in terms of transporting caloric which is supposed to be carried around by steam that cycles through the engine. This conception enables him to explain the functioning of the steam engine:

> “So what exactly happens in a steam engine of the kind now in use? Caloric produced in the furnace by combustion passes through the walls of the boiler and creates steam, becoming in a sense part of it. The steam bears the caloric along with it, transporting it first into the cylinder, where it fulfils a certain function, and then into the condenser. There, the steam is liquefied by contact with the cold water it encounters. In this way, at the end of the whole process, the cold water in the condenser absorbs the caloric produced by the initial combustion: it is heated by the steam just as if it had been in direct contact with the furnace. The steam serves simply as a means of transporting the caloric, ... we are considering the movement of the steam is put to use.” (ibid. p. 64)

The functioning of the heat engine is thus brought under his newly developed conception of heat. Yet, the citation presents us also with a more full-blown description of the target phenomenon that he aims to model. Clearly, this is a scientific conception of the target phenomenon, which affords (i.e., makes scientifically accessible) the further modelling of the functioning of the heat engine and finding out about its theoretical limits. Consequently, what Carnot has in this point amounts already to a preliminary model, which, so far, entails the epistemic aim of the model and a scientific conception of the target phenomenon. The target phenomenon must be modelled in such a way that the epistemic aim will be met. As we will see, this preliminary model of the real heat-engine functions as an epistemic tool for the further development of the model, affording and constraining its further development.

Step IV. Conception of relevant (theoretical) principles

Carnot proceeded in his modelling endeavour by introducing propositions and principles that relate the scientific conception of the transport of heat (caloric) and the production of motive power, to relevant measurable parameters such as temperature, volume, and compression or expansion of the gas in the steam engine. In this way he also ties scientific aspects that are built in the model, to data that can be observed or measured in the real world. Some of these principles are definitions (e.g., a), others experiential (e.g. b) or experimental (e.g., g), and yet others theoretical (e.g. c, d, e, f, h). His development of these propositions and principles is reconstructed and summarized in the list below (ibid pp. 64-67).

> Carnot presents a definition of heat engines that draws on the scientific conception of it:
>
> a. The heat-engine is any engine that is driven by caloric.
>
> Important for proceeding the modelling is his articulation of an experiential principle:
>
> b. Equilibrium restores wherever a difference in temperature exists.
>
> Carnot develops this experiential principle further by bringing it under his scientific conception of heat (caloric), resulting in several theoretical principles (c,d,e,f):
>
> c. Caloric will always flow from a hot body to a cold body until the two bodies have the same temperature, by which equilibrium is restored.
>
> Therefore:
>
> d. In steam engines motive power is produced by the re-establishment of the equilibrium of caloric, not by consumption of caloric,
>
> and:
>
> e. Whenever there is a difference in temperature, motive power can be produced,
>
> while the converse is also true:
>
> f. Wherever there is power which can be expended, it is possible to bring about a difference in temperature and to disturb the equilibrium of caloric.
>
> Additionally, it is an experimentally well-known fact that:
>
> g. The temperature of gaseous substances rises when they are compressed, and falls when they are expanded.
>
> From these principles he infers to 'an obvious' principle that:
>
> h. Heat can only be a source of motion in so far as it causes substances to undergo changes in volume or shape.

What we have seen so far, in Carnot's modelling, is that he has built in the model several elements by conceptualizing and creative reasoning with these new concepts, towards additional conceptualizations. A way of describing what he does is that he draws on some 'conceptually bare' experiential or experimental knowledge, and enriches this knowledge by bringing it under his new concepts (e.g., his theoretical conception of heat, and of how heat produces motive force). In this manner, he produces new ways of imagining what is going on. Importantly, these enriched imaginations and conceptualizations do not have their source in additional observations or experiments.

Step V. Conception of a hypothetical device:

Again, the model in its present state, which now has built into it this list of principles, functions as an epistemic tool that guides and constrains its further development. What this means, for instance, is that Carnot in his creative reasoning uses these explicitly articulated principles for conceiving of the working of a hypothetical device. They also enable to abstract from features of the real steam engine that in his view are not essential to a theoretical understanding of how a steam engine produces motive power by heat (that is, by the transfer of caloric through the engine). Accordingly, he abstracts from concrete components such as the furnace and the condenser by asking the reader to “imagine” two bodies, A and B (the temperature of A is higher than B), to which heat (caloric) can be added or from which it can be taken away without effecting any change in their temperature, and which will act as two infinite reservoirs of caloric. The articulated principles play a role in enabling Carnot to come up with a more abstract as well as a more analytic conception of the functioning of the heat-engine (that is, a conception of how the heat-engine produces motive power from heat, i.e., a conception of the target phenomenon). To start with, Carnot conceives of a hypothetical device as consisting of three operations (ibid pp. 67-68). Carnot states:

> “If we wish to produce motive power by conveying a certain amount of heat from the body A to the body B, we may do this in the following way:
>
> (i) Take some caloric from the body A and use it to form steam. In other words, use the body as if it were the furnace. It is assumed that the steam is produced at precisely the temperature of the body A.
>
> (ii) Pass the steam into a vessel of variable volume, such as a cylinder fitted with a piston, and then increase the volume. When the steam is expanded this way, its temperature will inevitably fall. Suppose that expansion is continued to the point where the temperature becomes exactly that of body B.
>
> (iii) Condense the steam by bringing it into contact with B, and, at the same time, subjecting it to a constant pressure, until it is totally liquefied. In this way, B fulfils the role of the injection water in a normal engine.”

How, exactly, does Carnot use the model for developing this hypothetical device? Although Carnot does not make explicit how he employs the former principles (our list, a-h), their role can be reconstructed. Let us first figure out in what sense this latter conception of the device differs from the former (ibid. 64). The former conception of the target phenomenon basically describes how the caloric is transferred in a cycle through the heat engine (from furnace to steam to cylinder to condenser to cold water). Carnot proceeds on this conception by simplifying the device, thus making it more abstract. The former device consisted of a furnace, a boiler, a cylinder with steam in it closed with a movable piston, a condenser, and a reservoir of cold water, whereas the latter reduces to the cylinder closed with a movable piston and two sources of caloric – in this latter device no more cooling-water is involved for condensing the steam. This simplification of the device is directly related to aiming at carving up the cycle in imaginable distinct operations. In constructing these distinct operations produced by a simplified, hypothetical device, Carnot uses the principles in order to relate the transfer of caloric to (changes in) temperature and volume of the steam in the cylinder. This results in imagined operations brought about by the simplified, hypothetical device, which can be summarized as follows: (i) caloric is transferred from body A to form steam at temperature A; (ii) the steam expands in the cylinder by which the temperature falls to B (use of principles f and g); (iii) the steam is compressed to form water at temperature B; the increase of temperature (according to principle f and g) is prevented by transfer of caloric from steam to body B (principle b and c) to form water at temperature B.

Step VI. Introduction and use of an abstract concept: reversibility of processes:

However, at this point, only half of the cycle through which the hypothetical device must go, has been constructed by the operations described in i, ii, iii. For closing the cycle, the ‘liquefied steam’ at temperature B (in iii) must be brought back to temperature A. This could be easily achieved by heating the ‘liquefied steam’ to temperature A, as it may happen in a real heat-engine. However, at this point, Carnot makes a brilliant conceptual leap by introducing a notion of *reversibility* of processes. This notion helps him further towards finding out how a hypothetical device could possibly produce the maximum amount of motive power – which at this stage of the modelling is understood as the maximum amount of volume change in the cylinder relative to the amount of heat-use. Again, this new conception is made possible by the model at its present state.

How does the model in its present state enable Carnot's conception of reversibility? In presenting this notion of reversing a process, Carnot states that there is no reason "why we should not form steam with caloric from the body B and at the temperature of B, compress it so as to bring it to the temperature of A, continuing the process of compression until complete liquefaction takes place" (ibid p. 68). Carnot thus conceives of how the cycle can be closed by reversing the process such that the steam in the cylinder is brought back to its initial state.

We can easily follow Carnot in imagining at an abstract level that operations i, ii, iii, could possibly be reversed. However, what is remarkable and brilliant about it, is that this reversal does not draw on concrete experiential or experimental knowledge of the processes described in this latter quote. Rather to the opposite, experiential and experimental knowledge of that time would hinder any such imagination, for it was not easy to imagine, for instance, that steam could be formed from water at temperature B by a cold body at temperature B (which is what actually happens in refrigerators). The introduction and use of this abstract concept is a clear example of how creative reasoning works. Such reasoning is made possible by bringing knowledge (i.e., the knowledge that has been systematically and explicitly brought together in the model) under an abstract concepts (reversibility), leading to new conceptions (forming steam at a low temperature by transfer of caloric to it). Scientists do not easily arrive at such new conceptions from mere experience.

Nevertheless, having developed a conception of the reversible process, of course raises the question why we should believe that the reverse process is *physically* possible as well? Indeed, in order to explain how this would work physically, the conception of the reverse process needs to be fleshed-out much further. This is what actually happens in further modelling.

Step VII. Conception of principles for producing the maximum amount of motive power, i.e., principles for avoiding losses:

These kind of imagined possible operations (i, ii, iii and reverse) help Carnot in constructing a cycle that produces the maximum amount of motive power. Note that the construction of that cycle does not aim at representing the cycle in the real heat engine, but instead, at an imagined cycle (the hypothetical device) in which the loss is minimized. Enabling the construction of a cycle of operations that produces the maximum amount of motive power first requires to account for the possible causes of loss. Accordingly, by using the model in its current state, in particular the former principles (a-h), Carnot develops some additional principles that explain losses (and avoidance of losses) in the production of motive power by heat. These principles are listed by us:

i. Since any process in which the equilibrium of caloric is restored can be made to yield motive power, a process in which the equilibrium is restored without producing power must be regarded as representing a real loss.

From reflecting on this latter point, Carnot concludes:

j. Any change in temperature that is not due to a change in the volume of a body is necessarily one in which the equilibrium of caloric is restored profitlessly.

Hence:

k. The necessary condition for the achievement of maximum effect is that the bodies used to produce motive power should undergo no change in temperature that is not due to a change in volume.

However:

l. When a gaseous fluid is rapidly compressed, its temperature rises; and when, on the other hand, it is rapidly expanded, there is a fall in temperature.

What becomes obvious from these latter principles (i-l) is that Carnot must construct a cycle in which change in temperature without change in volume (j) is avoided, as well rapid compression or expansion (l).

Step VIII. Constructing the ideal heat-engine

Carnot now has a model of the heat-engine, which holds together the epistemic aim, and a conception of the target phenomenon (i.e., the hypothetical device that consists of a cylindrical vessel closed with a movable piston that encloses a constant amount of steam – in which the gas can be either thermally isolated, which means that there is no transfer of caloric, or contacted with body A at a constant high temperature that acts as a source of caloric (heat), or with a body B at a constant low temperature that acts as sink of caloric (heat) –, which goes through cycle i, ii, iii, and reverse), as well as knowledge by which he can construct possible operations (i.e., principles a-h), and knowledge about causes of loss (i.e., principles i-l). Carnot uses this model as an epistemic tool for finding out how to construct a cycle that will produce the maximum amount of motive power. That is, he uses the model at this stage for constructing a hypothetical device called the ideal heat engine.

As we already have illustrated in the former section (Step VI), Carnot's approach entails using the model for imagining different kinds of possible operations with the hypothetical device. He constructs these imagined operations, for instance, by using his understanding of caloric (presented in the former principles) and the important experiential principle that gas undergoes change in T as a result of compression or expansion (principle g). Carnot imagines, for instance, how the temperature can be changed without changing its volume by withdrawing or supplying caloric. According to principle j, this is an operation that causes loss, which therefore must be avoided in the ideal heat engine. Carnot also argues that it would be equally possible to withdraw caloric during the process of compression in such a way that the temperature of the gas would remain constant, which implies that the rise of temperature that would be due to rapid compression (principle l) can be avoided. Likewise, if the gas is expanded, its temperature can be prevented from falling if we supply to it an appropriate quantity of caloric. (ibid. 72).

We claim that such operations result from using the model as an epistemic tool, and could not possibly be derived from mere experience with real steam engines. Again, by these examples of constructive activities in the modelling we aim to illustrate our claim that models must be understood as epistemic tools that are co-constructed together with conceptions and imaginations, neither of which are to be understood as primarily having a representational relationship to objects in the real world.

As stated, Carnot makes use of these kinds of imaginations of possible operations for constructing a hypothetical cycle that avoids losses, which, as he knows by now, must be constructed such that the problem of "restoring caloric profitlessly" is avoided by preventing that "changes in temperature occur that is not due to a change in volume". He further simplifies the hypothetical device by using gas instead of steam, and proposes a hypothetical cycle of four operations that is supposed to produce the maximum amount of motive force. The description of the four operation of the ideal heat engine refer to the schema of the cylinder with piston that can be contacted with body A and B (Figure 1):

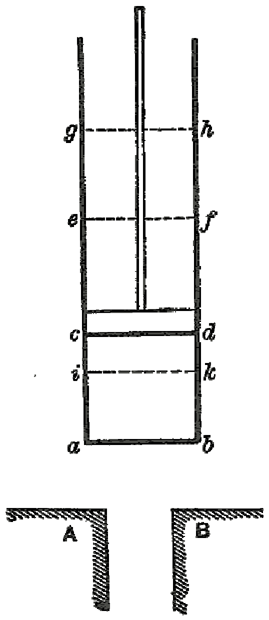

Figure 1. (ibid. p. 114) Axial cross section of the hypothetical device, which is part of the Carnot model of the heat-engine. In this diagram, *abcd* is a cylindrical vessel, *cd* is a movable piston, and *A* and *B* are constant–temperature bodies that act as source or sink of caloric. The vessel may be placed in contact with either body or removed from both (as it is here).

> (1) The air is placed in contact with the body B. It is then compressed by returning the piston from its position *gh* to *cd*. During this process, the air maintains a constant temperature, since it remains in contact with B and gives up caloric to it.
>
> (2) The body B is taken away, and the compression of the air is continued. Since the air is now isolated, its temperature rises. Compression continues until the temperature of the air reaches that of the body A, by which time the piston has moved from the position of *cd* to *ik*.
>
> (3) The air is placed once again in contact with the body A, and the piston returns from *ik* to *ef*; the temperature remains constant.
>
> (4) A is removed, so that the air is no longer in contact with any body that can act as a source of caloric. But the piston continues to move, rising from the position *ef* to *gh* The air expands without absorbing caloric, and its temperature falls. Let us *suppose* that the temperature continues to fall until it is equal to that of B, whereupon the piston stops at the position *gh*.

It can easily be seen, how this description of the cycle draws on the previously developed conceptions of possible operations. Hence, Carnot's model of the ideal heat-engine, finally consists of the epistemic aim, the knowledge such as presented in principles a-l, and the final conception of the ideal heat-engine, which is a hypothetical device that is supposed to produce motive force at minimum loss (i.e., the maximum amount of motive force that can be produced by heat-engines).

Summing up

In our discussion of the Carnot model we have aimed to show that the Carnot-model of the ideal heat-engine is not constructed as a *representation* of actual heat-engines by some kind of obvious resemblance or similarity with it, for instance, as about its mechanical working, or as about the observable or measurable properties of real heat engines. This is contrary to what some versions of the pragmatic and semantic views of models would suggest. Rather, the Carnot-model is constructed as an hypothetical engine affording reasoning in view of a certain purpose. In our reconstruction, we have focussed, firstly, on the crucial role conceptualization plays in modelling, and secondly on the idea that generally, there are not some kind of pre-established (already justified) elements that are built into the model, but instead, that modelling consists of a co-construction of different elements that mutually develop in modelling and in the meanwhile are held together by the model. These constructed elements are for instance, (1) the epistemic aim of the model, usually related to a question or problem; (2) the idealizations, abstractions and simplifications that make the real target system intelligible and workable; (3) the target phenomenon into which the original problem is translated; (4) the particular representational forms with the help of which the imaginary (or hypothetical) target system is represented; (5) the experiential and theoretical knowledge used in the modelling; (6) the concepts, principles and conceptualizations that may emerge in the modelling; and (7) the relevant observable or measurable parameters of the real target system which link the scientific model to it. We claim that this intricate content of scientific models, which usually is fully understood only by the scientists working in the field in question, makes models to function as epistemic tools.

5. Concluding remarks

How do models give us knowledge? We have claimed that this happens through the construction and use of concrete artefacts, models, that are expressed with different representational means. It seems to us that the key to the epistemic value of models is the process of modeling rather than some determinable representational relationship between a ready-made model and its putative real target system. We have shown with the example of the Carnot model of the heat engine that in the process of modeling the model construction coincides with the creation (and discernment) of phenomena, and the development of theoretical concepts and principles. While the idea of such co-construction of phenomena, theoretical concepts and principles is by no means novel, it has not really entered the discussion on modeling in the philosophy of science. This may seem odd at the outset, since models are typically delegated the roles of scientific discovery and theory construction in philosophical discourse. However, it seems to us that the prevailing representational approach to models offers an explanation for this neglect. The idea of capturing the objective nature of real target systems (either by similarity or by a morphism of some kind) seems to be built into the representational approach. Such perspective is at odds with the idea of co-construction of the theoretical model and its target system.

While the pragmatic approaches to representation do not seek such an objective representational relation that would link the model and the target irrespective of the representers' intentional activity, they have focused so far in the use of ready-made representations. To be sure, Giere (2006) and van Fraassen (2008) have pointed out the importance of the creation of phenomena as a part of their pragmatic approaches to representation. This does not save, however, the pragmatic accounts of representation from its minimalism, which implies that it cannot be expected to do any significant philosophical work in explaining in virtue of what do we gain knowledge through models. We do not regard this, however, as an inherent deficiency of the pragmatic account of representation, since to expect a philosophical analysis of representation to ground our knowledge claims seems to us a mission impossible. Consequently, our critique against the representational account of models is not geared against the possibility of representation per se, we have rather argued that representational approach to models does not succeed in delivering what it is commonly taken to establish.[viii]

While models make part of the class of cultural artefacts called representations, from our point of view establishing a *representational relationship* between a model and a part of the world is already a remarkable epistemic achievement – it is thus the activity of modeling that forges the link between the representational vehicle -- the model -- and the represented. The key to the mystery of representation is the process of co-construction, in which process the model, the phenomena, the theoretical concepts and principles are developed concurrently. We have suggested that the model as a concrete evolving object functions as a tool in integrating and guiding this process. All these aspects of modeling can be considered as epistemic results of modeling and not just the ensuing representational relationship. Furthermore, the model does not function as an epistemic tool because of some determined representational relationship, but functions rather as a tool in establishing it – apart from functioning as a tool for scientific reasoning. However, once a representational relationship becomes established, we tend to become forgetful of this co-constructive process by which it came into being. This is where the philosophical wrestling with representation tends to start.

Literature

Ambrosio, C. (2007), *"Iconicity and Network Thinking in Picasso's Guernica: A Study of Creativity across the Boundaries".* Unpublished PhD thesis, University College London.

Bailer-Jones, D. M. (1999),"Tracing the Development of Models in the Philosophy of Science", in Lorenzo Magnani, Nancy J. Nersessian and Paul Thagard (eds.), Model-Based Reasoning in Scientific Discovery. New York: Kluwer, 23-40.

Bailer-Jones, D. M. (2003), "When Scientific Models Represent", International Studies in the Philosophy of Science 17: 59-74.

Bartels, A. (2006), "Defending the Structural Concept of Representation", Theoria 55, 7-19.

Boon, M. (2006), "How Science is applied in Technology", International Studies in the Philosophy of Science 20(1): 27-47.

Boon M. (2009), "Understanding according to the Engineering Sciences: Interpretative Structures", in Henk De Regt et.al. (eds.), Scientific Understanding: Philosophical Perspectives, University of Pittsburgh Press, 249-270.

Boon, M. and T.T. Knuuttila (2009). Models as Epistemic Tools in Engineering Sciences: A Pragmatic Approach. in: Handbook of the Philosophy of Technological Sciences, Anthonie Meijers (ed.), Amsterdam, Elsevier Science. 687-719.

Boumans, M. (1999), "Built-In Justification", in Mary S. Morgan and Margaret Morrison (eds.), Models as Mediators. Perspectives on Natural and Social Science. Cambridge: Cambridge University Press, 66-96.

Carnot, S. (1986, [1824]), "Reflexions on the Motive Power of Fire." Translated and edited by Robert Fox, New York, Manchester University Press.

Clausius, R. (1865), "The Mechanical Theory of Heat – with its Applications to the Steam Engine and to Physical Properties of Bodies." London: John van Voorst, 1 Paternoster Row. MDCCCLXVII

Clausius, R. (1899, [1850]]. "On the Motive Power of heat, and on the Laws which can be Deduced from it for the Theory of Heat". In: The Second Law of Thermodynamic. Memoirs by Carnot, Clausius and Thomson. New York and London, Harper & Brothers Publishers.

da Costa, N. C. A. and S. French (1990), "The Model–Theoretic Approach in the Philosophy of Science", Philosophy of Science 57: 248–265.

Erlichson, H. (1999), "Sadi Carnot, 'Founder of the Second Law of Thermodynamics.' European Journal of Physics 20: 183-192.

Clark, A. (1997), Being There: Putting the Brain, Body, and World Together Again. Cambridge, MA: MIT Press.

French, S. (2003). A Model-Theoretic Account of Representation (Or, I Don’t Know Much About Art…but I Know It Involves Isomorphism). Philosophy of Science, 70, 1472-1483.

French, S. and J. Ladyman (1999), “Reinflating the Semantic Approach”, International Studies in the Philosophy of Science 13,2: 103-121.

Frigg, R. (2002), Models and Representation: Why Structures Are Not Enough. Measurement in Physics and Economics Discussion Paper Series. London: London School of Economics.

Frigg, R. (2006), ”Scientific Representation and the Semantic View of Theories”, Theoria 55, 49-65.

Giere, R. N. (1988), Explaining Science: A Cognitive Approach. Chicago and London: The University of Chicago Press.

Giere, R. N. (1999), Science without Laws. Chicago and London: The University of Chicago Press.

Giere, R. N. (2002), “Scientific Cognition as Distributed Cognition”, in Peter Carruthers, S. Stich and M. Siegal (eds.), Cognitive Bases of Science. Cambridge: Cambridge University Press.

Giere, R. N. (2004), “How Models Are Used to Represent Reality”, Philosophy of Science (Symposia) 71: 742-752.

Giere, R.N. (2006), Scientific Perspectivism. Chicago University Press.

Godfrey-Smith, P. (2006), “The Strategy of Model-Based Science”, Biology and Philosophy 21: 725-740.

Hacking, I. (1983), Representing and Intervening. Cambridge: Cambridge University Press.

Humphreys, P. (2004), Extending Ourselves. Computational Science, Empiricism and Scientific Method, Oxford: Oxford University Press.

Knuuttila, T. (2005), “Models, Representation, and Mediation”, Philosophy of Science 72: 1260-1271.

Knuuttila, T. and Merz, M. (forthcoming), “An Objectual Approach to Scientific Understanding: The Case of Models”, In Henk de Regt, Sabina Leonelli and Karl Eigner (eds.) Scientific Understanding: Philosophical Perspectives. Pittsburgh: University of Pittsburgh Press.

Knuuttila, T. and Voutilainen, A. (2003), “A Parser as an Epistemic Artefact: A Material View on Models”, Philosophy of Science 70: 1484–1495.

Kroes, P. (1995), “Technology as Science-Based Heuristics.” In J.C. Pitt (ed.): New Directions in the Philosophy of Technology.”. Kluwer Academic Publishers: 17-39.

Larkin, J. and Simon, H. A. (1987), “Why a Diagram is (Sometimes) Worth 10,000 Words”, Cognitive Science, 11:65-99.

Lynch, M. (1990), “The Externalized Retina: Selection and Mathematization in the Visual Documentation of Objects in Life Sciences”, in M. Lynch and S. Woolgar (eds.), Representation in Scientific Practice. Cambridge, MA: MIT Press, 153-186.

Mattila, E. (2006): *Questions to Artificial Nature: A Philosophical Study of Interdisciplinary Models and their Functions in Scientific Practice*. Philosophical Studies from the University of Helsinki, 14. Dark: Helsinki.

Merz, M.(1999), “Multiplex and Unfolding: Computer Simulation in Particle Physics”, *Science in Context* 12 (2): 293-316.

Morrison, M. (1999), Models as Autonomous Agents, in Mary S. Morgan and Margaret Morrison (eds.), Models as Mediators. Perspectives on Natural and Social Science. Cambridge: Cambridge University Press, 38-65.

Morrison, M. and M. S. Morgan (1999b), "Models as Mediating Instruments", in Mary S. Morgan and Margaret Morrison (eds.), Models as Mediators. Perspectives on Natural and Social Science. Cambridge: Cambridge University Press, 10-37.

Nersessian, N. J. (2008), Creating Scientific Concepts, Cambridge, MA: The MIT Press.

Portides, D. P. (2005), "Scientific Models and the Semantic View of Scientific Theories" Philosophy of Science 72: 1287-1298.

Suárez, M. (1999), "Theories, Models, and Representations", in L. Magnani, N. J. Nersessian and P. Thagard (eds.), Model-Based Reasoning in Scientific Discovery. New York: Kluwer, 75-83.

Suárez, M. (2003), "Scientific Representation: Against Similarity and Isomorphism", International Studies in the Philosophy of Science 17: 225-244.

Suárez, M. (2004), "An Inferential Conception of Scientific Representation", Philosophy of Science (Symposia) 71: 767-779.

Suppe, F. (1974), The Structure of Scientific Theories. Urbana, University of Illinois Press.

Suppe. F. (1989), The Semantic Conception of Theories and Scientific Realism. Urbana and Chicago, University of Illinois Press.

Teller, P. (2001), "Twilight of the Perfect Model Model", Erkenntnis 55: 393-415.

Van Fraassen, B. (1980), The Scientific Image. Oxford: Oxford University Press.

Van Fraassen, B. (2008), Scientific Representations, Paradoxes and perspectives. Oxford: Oxford University Press.

Vorms, M. (2009), "Formats of Representation in Scientific Theorising", in PhilSci Archive: [2009] *Models and Simulations 3* (Charlottesville, Virginia; March 5-7, 2009): http://philsci-archive.pitt.edu/archive/00003901/

Weisberg, M. (2007), "Who is a Modeler", British Journal for the Philosophy of Science 58: 207-233.

Zhang, Jiajie (1997), "The Nature of External Representations in Problem Solving", Cognitive Science 21(2): 179-217.

Acknowledgements

This research is supported by a grant from the Dutch National Science Foundation (NWO) and the Academy of Finland.

Notes

---

[i] Van Fraassen (2008) accounts for this feature of maps as their "inevitable indexicality of application".

[ii] For other properties that we might expect an acceptable concept of representation to satisfy, see Suarez (2003) and Frigg (2002, 2006)

[iii] The actual representational means used in modelling is strangely neglected topic in the discussion on models and representation. See however Vorms 2009.

[iv] In this respect our approach comes close to Mattila's work on simulation models as "artificial nature" constructed to answer some pertinent questions.

---

[v] In a previous article (Boon and Knuuttila, 2009) we have presented an extended, more technical analysis of Carnot's work. The approach in the present article is different as to (1) emphasis on the role of conceptualizing in modelling, in general, and (2) emphasis on the co-construction of the target phenomena, theoretical conceptions and model.

[vi] An example of a (moving) picture that represents the mechanical working of a specific type of heat engine (the Newcomen steam engine) can be found under this link: http://en.wikipedia.org/wiki/Newcomen_steam_engine

[vii] This reconstruction of Carnot's conception of heat, in part was found in Clausius' (1864, 1899) *Memoirs on Carnot*.

[viii] One reading of the representational account of models, in line with the semantic version of it, is that the analysis of representation does not even try to explain how models give us knowledge but rather functions as a justificatory account. Thus, on that account, the analysis of representation is supposed to give us a criterion for the success of the model. From our perspective the semantic account does not fare well even in this respect because the justification of a model gets largely built into it in the process of modeling. In this process the model is not just justified by the initial justification its ingredients might have, but also through the new theoretical and conceptual content born in the process of modeling.