MODELS AS EPISTEMIC TOOLS IN ENGINEERING SCIENCES

Mieke Boon and Tarja Knuuttila

1 INTRODUCTION

When browsing through scientific journals in the field of engineering sciences, we soon learn that models play a central role in them. Through modelling, engineering sciences strive to understand, predict or optimize the behaviour of devices or the properties of diverse materials, whether actual or possible. The models developed in the *engineering sciences* should be distinguished from the models produced in *engineering*. Whereas the latter usually represent the design of a device or its mechanical workings, models in the engineering *sciences* aim for scientific understanding of the behaviour of different devices or the properties of diverse materials. For instance, chemical engineering is concerned with designing processes for converting materials or chemicals into other materials and chemicals that meet certain functions or purposes. For these processes it uses devices, such as chemical reactors and equipment for separation of substances such as crystallization, precipitation, absorption, filtration and distillation. *Scientific* research in the field of chemical engineering proposes models of the *behaviour* of chemical devices. It typically proceeds to study the behaviour of devices by interpreting them in terms of physical phenomena considered to be relevant to their proper or improper functioning, and then modelling these phenomena. Examples of such phenomena are desired and undesirable chemical reactions, the transport of liquids, gasses and solids within the device, the transport of chemical compounds by means of fluid flow or diffusion in the fluid, the transport of heat by convection or conduction, and other physical processes such as absorption, dissolution, ionization, precipitation, vaporization and crystallization. In the scientific literature, authors typically propose a certain type of design of the device — which consists of a configuration (e.g. a schema of its mechanical construction and dimensions) and its chemical and physical conditions — for meeting a certain function, for instance, for producing a compound at a high purity and with a minimum of waste production and energy use.

Likewise, electrical *engineering* is concerned with designing devices — such that convert or transform electrical, electro-magnetic or mechanical input into electrical, electro-magnetic or mechanical output that meets certain functions. As in

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the case of chemical engineering, *scientific* research in the field of electrical engineering proposes models of the *behaviour* of electrical devices, which task differs from the *design* (e.g. of electrical circuits) of such devices. Also in this scientific field, scientific articles aim to contribute to optimizing the devices with regard to their functioning. Or, to take a third example, materials *engineering* is concerned with the application of materials with properties (e.g. chemical, electrical or mechanical properties) that meet certain functions. For instance, metals which are resistant to corrosion, ceramics that are superconductive at higher temperatures, and polymers of a particular strength. Materials *science* is concerned with scientific understanding of materials — either of materials that already exist or of materials that scientists aim to create artificially — which may then indicate ways in how to create or intervene with specific material properties.

As the examples above show, the engineering sciences aim at both furthering the development of devices and materials meeting certain functions and optimizing them. Through modelling the engineering scientist seek to gain understanding of the behaviour and properties of various devices and materials. More often than not, this involves conceiving the *functioning* of the device, often in terms of particular *physical phenomena that produce the proper or improper functioning of the device.* However, in many cases, the *desired properly functioning* devices and materials do not exist. In these cases, the scientific models function as tools for producing such devices and materials.

To understand engineering sciences and the way they use modelling to optimize and create devices and materials to meet specific functions, we need an account of how scientific models are produced and used in scientific practice. In particular this involves making sense of how models in engineering sciences acquire cognitive value with respect to their very orientation towards the artifactual, in other words, how models enable scientists to reason through constructing and using them. For this task a mere representational approach to models proves too limiting.

In the philosophy of science it is generally accepted that scientific models *represent* some aspects or parts of the world or, more specifically, some real target systems. This idea of models as representations has been given different formulations ranging from semantic to pragmatist accounts of representation. According to the semantic conception of representation models are structures that represent the structural properties of real target systems as they feature in experimental and measurement reports by being either isomorphic or similar to them. From the pragmatist perspective this amounts to approaching research from the finished science point of view — yet it seems more apt to conceive especially engineering scientists as active interveners with the world. Instead of depicting an already existing world, the engineering sciences aim at theories and models that provide understanding of *artificially created* phenomena. This role of engineering sciences seems to us better accommodated by a pragmatic view on them. Indeed, as we will show below, the pragmatic approach to representation in fact points to a more versatile understanding of models than what a mere representational approach to them grants.

In the following we will consider scientific models in engineering as *epistemic tools* for creating or optimizing concrete devices or materials. From this pragmatist and functional perspective, scientific models appear as things that are used by scientists to do some *work*, in other words, to fulfil some purposes. Consequently, we approach modelling as a specific scientific practice in which concrete entities, 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 other artifacts and instruments. The key to the epistemic value of models does not lie in their being accurate representations of some real target systems but rather in their independent systemic construction that enables scientists to draw inferences and reason through constructing models and manipulating them. Although this way of looking at models makes sense especially in the context of engineering sciences because of their intervening and constructive character, we suggest that it could be applied to other sciences as well.[1] In this sense engineering sciences might even serve to highlight some characteristics of scientific modelling and representation in general, especially if engineering sciences are firmly distinguished from engineering (see above). This chapter thus aims also to give an overview of the various accounts of scientific models and representation in the philosophy of science, and to show in which directions these approaches have recently been extended in order to capture the role of scientific models in scientific practices better.

We will proceed as follows and start by presenting an overview of the present discussion of models and representation in the philosophy of science, and explicating how the conception of models as epistemic tools fits into this more overall picture (Section Two). In turn this general discussion on models provides us with a background for analysing the Carnot model of the heat-engine, which, as we will argue, can still serve as a paradigmatic case of modelling in engineering sciences (Section Three). The final section draws together the themes of this chapter and points out different topics that an extended understanding of models should take into account (Section Four).

2 SCIENTIFIC MODELS IN PHILOSOPHY OF SCIENCE: FROM REPRESENTATIONS TO EPISTEMIC TOOLS

Judging by their virtual absence from the general philosophical discussion on modelling, models in engineering sciences have not qualified as worthy objects of study. This may be due to the tendency of the philosophers to relegate the engineering sciences to the realm of application. However, there is at present an intense discussion going on in the philosophy of science concerning models and modelling which is largely due to their constantly rising importance in contemporary science. As a result, new accounts of models and their epistemic or cognitive value have been

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[1] Hacking [1983] argues that science in general should be seen as an intervening rather than representing enterprise. These kinds of claims have also been repeatedly presented in the field of Science and Technology Studies, although not in the form of a philosophical argument.

presented that also seem to suit modelling in the engineering sciences better. In the following we will shortly review this discussion in an attempt to show that the emphasis on representation places excessive limitations on our view of the knowledge-bearing nature of models. As an alternative we suggest that models could be approached as epistemic tools.

2.1 Models as representations

The discussion on models in the philosophy of science has heterogeneous beginnings. It testifies to both theoretical and formal, as well as practical aspirations, which can be seen to have different and even conflicting goals [Bailer-Jones, 1999, 32]. Thus in parallel with approaches which focus on the pragmatic and cognitive role of models in scientific enterprise, there have been attempts to establish, within a formal framework, what scientific models are. Of the formal approaches the semantic conception was the most widely held conception of models for several decades, since its emergence in the early sixties. Yet it can be claimed that the very philosophical discussion of models has been importantly motivated by practice-oriented considerations — even the proponents of the semantic theory understood themselves as providing a more realistic picture of theories (see [van Fraassen, 1980, 64]).

Although there have thus been differing perspectives on models, philosophers of science have still generally agreed that models are representations and as such they give us knowledge because they represent their supposed external target objects more or less accurately, in relevant respects [Bailer-Jones, 2003; da Costa and French, 2000; French and Ladyman, 1999; Frigg, 2002; Morrison and Morgan, 1999; Suárez, 1999; Giere, 2004]. Yet due to their general approach to models, different philosophers have presented widely diverging accounts of representation. The fundamental dividing line goes between those accounts that take representation to be a two-place relation between two things, the model and its target system, and the pragmatist ones according to which also the representation-users and their purposes should be taken into account, thus arguing for at least three-placed analysis of representation.

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. Recently, the semantic conception has been defended, for instance, by da Costa and French [2000], and French and Ladyman [1999]. 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 the 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 to each other [van Fraassen, 1980, pp. 45, 64; Suppe, 1974, pp. 97, 92; French, 2003; French and Ladyman, 1999]. 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. (Other candidates offered for the analysis of representation by the proponents of the semantic view are similarity [Giere, 1988] and homomorphism [Bartels, 2006].)

The above-mentioned theoretical attractiveness of isomorphism vanishes once we realize that the parts of the real world we aim to represent are not "structures" in any obvious way, at least not in the sense required by the semantic account. 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. This has, of course, been noticed by the proponents of the semantic theory. Patrick Suppes [1962] has, for instance, invoked "models of data" in order to account for the fact that isomorphism concerns the relation between structures, not the relation between raw data and theory. Thus the isomorphism required by the semantic account actually concerns the relationship between a theoretical model and an empirical model, the theoretical model being the model that satisfies the equations of the theory [Suppe, 1989, 103–106].

Even if we disregard the problem that the world does not present itself to us in ready-made structures, isomorphism does not give us a satisfactory account of representation, because it does not capture some common features of representation. Firstly, isomorphism has wrong formal properties. For instance, isomorphism denotes a symmetric relation whereas representation does not: we want a model to represent its target system but not vice versa. Secondly, and more fundamentally, isomorphism is a relationship between two structures, whereas scientific representation assumes a relationship between a structure and a real world target system. Structural isomorphism is not sufficient for representation since the same structure can be instantiated by different systems and thus isomorphisms. 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]). From the scientific practice point of view, the idea that isomorphism establishes scientific representation seems inadequate, or at least unfruitful. The idea that representation is either an accurate depiction of its object or not a representation at all does not fit our actual representational practices. It is typical of scientific models that they are inaccurate in many ways. Indeed, the important role of idealizations, simplifications, approximations and tractability considerations in modelling seem difficult to account for from the semantic perspective; for further comment on these topics the readers might refer to Hodges's contribution to this volume. Moreover, it seems unacceptable to consider the cases in which isomorphism between the theoretical structure and intended real target system fails as un-representational.[2]

The pragmatic approaches, in turn, make representation less a feature of the models and their target systems themselves than an accomplishment of the representation users [Suárez, 2004; Giere, 2004; Bailer-Jones, 2003; Frigg, 2006]. These

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[2] For other properties that we might expect an acceptable concept of representation to satisfy, see Suárez [2003] and Frigg [2002; 2006].

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 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 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.

Pragmatic approaches to representation solve the problems of the semantic notion of representation mentioned above; the users' intentions both create the directionality needed to establish a representative relationship and introduce indeterminateness into the representative relationships (since human beings as representers are fallible). But this comes at a price. When representation is grounded primarily on the specific goals and representing activity of humans as opposed to the properties of the representative vehicle and the target object, as a result 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 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". Instead, Suárez builds his inferential account of representation directly on the very features of surrogate reasoning.

The formulation Suárez [2004, p. 773] gives to the inferential conception of representation is the following:

> A represents B only if (i) the representational force of A points towards B, and (ii) A allows competent and informed agents to draw specific inferences regarding B.

The "representational force", according to Suárez, is "the capacity of the source to lead a competent and informed user to a consideration of the target". Thus part (i) of the formulation postulates that the representational uses of the source are a result of intentional activity of competent and informed agents. Part (ii) of the formulation contributes to the objectivity that is required of scientific representation by assuming A to have the constitution that allows agents to correctly draw inferences from B. Yet Suárez resists saying anything about what kind of a relation there is supposed to be between the source and the target. Thus it is legitimate to conclude that for him models do not have any uniquely determinate relationship to the real world.[3]

The pragmatic minimalist approach to representation has rather radical consequences for how we conceive of models. 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. It is nevertheless important to be clear on what is established by the pragmatist account. In fact, it just points to the impossibility of giving a general *substantial* analysis of representation that would explain how knowledge, or information, concerning real target systems could be retrieved from the model (cf. Hodges in this volume). The pragmatists do not deny that many scientific representations can be traced back to some target systems, or that they can depict them more or less accurately at least in some respects — the clearest cases of such models being scale models and maps. However, if we adopt a pragmatic approach to models, the focus on representation only starts to seem unnecessarily limiting.

Apart from the general philosophical reasons mentioned above, there are also reasons stemming from the scientific practice that make us question the fruitfulness of representational paradigm as regards the epistemic value of models. Not the least of them is the fact that instead of functioning as straightforward representations of some "real" systems, 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.

The philosophical and empirical points made above are bound to make one ask whether there is any other angle than representation alone from which to approach the knowledge-bearing properties of models. Interestingly, largely apart from the very interest on the topic of models and representation, a new discussion on models has emerged that loosens the epistemic value of models from representing definite target systems and considers them as independent objects. This gesture, we suggest, makes room for the various roles the very same models can play in scientific endeavour and prepares the way for conceiving models as epistemic tools (see also [Portides, 2005]).

2.2 Models as epistemic tools

The idea of models as independent objects or entities has been expressed by several recent authors in various ways. Morrison [1999] and Morrison and Morgan [1999] have considered models as *autonomous agents* which are through their con-

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[3] This is reflected in the way models can be extended from one context of use to a rather different context of use. However, the applicability of models in other contexts is often limited and must be "handled with care". In our account of models as epistemic tools they incorporate knowledge about where and how they can be used in generating knowledge.

struction partially independent from theory and data. This is because, besides being comprised of both theory and data, models typically also involve "additional 'outside' elements" [Morrison and Morgan, 1999, 11]. Boumans [1999] for his part disentangles models from the theory-data framework altogether. In his study on business-cycle he shows how many different "ingredients" the model can be constructed of, such as analogies, metaphors, theoretical notions, mathematical concepts, mathematical techniques, stylised facts, empirical data and finally relevant policy views. From another perspective, Weisberg [2007] and Godfrey-Smith [2006] have also come to the conclusion that models should be treated as independent entities. For them independence means independence from certain real target systems. Thus, instead of conceiving independence in terms of the relationship of models to the theory and world, or data, they release models from representing any definite real target system. 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. As Godfrey-Smith has aptly put it, modelling can be characterized by the "deliberate detour through merely hypothetical systems" it makes use of [2006, 734].

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 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.

Considering scientific models from the functional perspective requires one to address them as *concrete objects* that are constructed for certain *epistemic purposes* and whose cognitive value derives largely from our *interaction* with them [Knuuttila and Merz, forthcoming]. Consequently, scientific models can be considered as multifunctional *epistemic tools* [Knuuttila, 2005; Knuuttila and Voutilainen, 2003]. The importance of our interaction with models is recognized by Morrison and Morgan [1999], who stress how we learn from models by constructing and manipulating them. However, it seems to us that they leave this important idea somewhat half-way. Namely, 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 autonomous; 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. Herein lies also the rationale for comparing models to experiments: in devising models we construct self-contained artificial systems through which we can make our theoretical conjectures conceivable and workable. This applies as well to mathematical models as to other kinds of models that are more readily seen as having a material dimension.

Also the very variation of the different kinds of models used: scale models, pictures, diagrams, different symbolic formulas and mathematical formalisms, suggests that the material dimension of models and the diverse representational means they make use of are crucial for their epistemic functioning. The representational means used have different characteristic limitations and affordances; one can express different kinds of content with symbols than with pictures, for example. From this perspective the diverse external representational means provide external aids for our thinking, which also partly explains what is commonly ascribed as the heuristic value of modelling (see [Giere, 2002]). Cognitive scientists have approached this importance of external representational tools for our cognition through the notion of *scaffolding*. 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]). Science provides the utmost human activity of creating and using representational tools for cognitive purposes. It is already a remarkable cognitive achievement to be able to express any mechanism, structure or phenomenon of interest in terms of some representational means, including assumptions concerning them that are often translated in a conventional mathematical form. Such articulation enables further theoretical findings as well as new experimental set-ups, but it also imposes its own limitations on what can be done with a certain model.

Another aspect of scaffolding provided by models is related to the way they help us to conceive the objects of our interest clearly and to proceed in a more systematic manner. Models are typically constructed in such a way that they constrain the problem at hand — which happens typically by way of idealizations and abstractions — thereby rendering the situation more intelligible and workable. As the real world is just too complex to study as such, models simplify or modify the problems scientists deal with. Thus, modellers typically proceed by turning the constraints (e.g. the specific model assumptions) built into the model into affordances; one devises the model in such a way that one can gain understanding and draw inferences from using or "manipulating" it. Yet the seeming simplicity of models disguises the various elements they incorporate, such as familiar mathematical functions, already established theoretical entities, relevant scientific knowledge, certain generally accepted solution concepts, the intended uses of a model, the epistemological criteria that are supposed to apply to it and so forth. All these things that are built into a model give it also certain original built-in justification [Boumans, 1999]. These aspects of models also explain, on the one hand, how they allow *certain* kinds of solutions and inferences, and on the other hand, how they can also lead to unexpected findings, thereby breeding new concepts and problems and opening up novel areas of research (for concept formation in sciences, see [Nersessian, 2008]).

We thus suggest that we gain knowledge through models typically by interacting with them, that is by building them, manipulating them, and trying out their different alternative uses — which in turn explains why they are regularly valued for their *performance* and their *results* or *output.* From the functional perspective, rather than trying to represent some selected aspects of a given target system, modellers often proceed in a roundabout way, seeking to build hypothetical model systems in the light of their anticipated results or of certain general features of phenomena they are supposed to *bring about.* If a model gives us certain expected results or replicates some features of the phenomenon, it provides an interesting starting point for further theoretical and experimental conjectures. This orientation towards the results brought about by models also accounts for why modellers frequently use the same cross-disciplinary *computational templates*, such as well-known general equation types, statistical distributions and computational methods (for the notion of computational template, see [Humphreys, 2004]). The overall usability of computational templates is based on the one hand on their generality and the observed similarities between different phenomena and on the other hand on their tractability. The purposes the model is constructed for and the computability considerations often override in modelling the strive for correct representation. Consequently, the very peculiarity of scientific models lies in their being concrete entities that are aimed at accounting for certain phenomena through the detour of constructing artificial entities keeping simultaneously in mind their intended uses and other pragmatic questions such as their computability. This holistic nature of models in fact distinguishes them from more elementary scientific representations such as different visual displays, which often further fragment the object or specimen to reveal its details (see [Lynch, 1990]).

Consequently, many scientific models should *not* be first and foremost considered as accurate representations of some target systems, but rather as epistemic tools. In an engineering context this amounts to finding out how to produce, control, and intervene — or to prevent some properties of materials or behaviour of processes and devices. Scientists 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). Often, these models also incorporate dimensions of typical configurations of certain devices. In the following section we will exemplify the functional approach to models by studying the Carnot model of the heat-engine. We highlight the purpose of the model, the way the original problem motivating the model construction was translated into a phenomenon to be accounted for by way of different constraints and representational means. We also argue that the consequent thermodynamic theory became possible through the construction of this model, and not vice versa, which stresses the epistemic importance of building models and working with them.

3 DEVELOPMENT AND EPISTEMIC USE OF SCIENTIFIC MODELS: THE CASE OF THE CARNOT MODEL OF A HEAT-ENGINE

The heat-engine is a classical example of a technological device that was subject to scientific modelling. We will analyse more closely how Carnot and his successors developed the Carnot model of the heat-engine. By this analysis we aim to illustrate that a pragmatic approach presents us with a more adequate picture of models and modelling than a paradigmatic representational view, in particular as regards how, in actual scientific practices, models are justified and why they give us knowledge. Carnot's *Reflexions on the Motive Power of Fire* [1824/1986] is particularly interesting as a case of scientific modelling in the engineering sciences because Carnot's treatise describes how step-by-step he develops a theoretical interpretation of a technological device. His writings expose the explorative reasoning process by which different aspects are built in the scientific model, which illustrates how it was constructed and justified. Scientific articles in our days often hide important parts of the reasoning process by which the model was developed. Nersessian and Patton (this Volume), for instance, meticulously describe many of the aspects scientists take into account in developing their models, many of which will not be part of scientific articles by these scientists. Besides the fact that Carnot exposes how he developed the model, the Carnot model of the heat-engine makes a good case because it is less complex than many of the appealing modern cases in the engineering sciences. Although historical, it still illustrates how engineering sciences approach technological problems. Moreover, it makes a better case than modern examples because many scholars in philosophy of technology are already familiar with the Carnot model (cf. [Kroes, 1995]). Last but not least, we take it that despite the enormous increase in scientific knowledge, mathematical and computational techniques, and scientific instruments, the way in which scientists develop scientific models of devices has not fundamentally changed.

3.1 The Carnot model of the heat-engine

According to the representational view, the Carnot model of the heat-engine is a scientific model that represents the real heat-engine. Our pragmatic view, on the contrary, targets *modelling* rather than just the entities called models, thus also making place for the role of the scientists and their epistemic purposes in accounting for the epistemic value of models. From this perspective Carnot's model is a constructed entity, which gives a theoretical interpretation of the heat-engine in view of particular epistemic purposes. One such important purpose was identifying the theoretical limits of the performance (efficiency, in modern terms) of the heat-engine. The turn to modelling thus actually implies an extended notion of a model: models can be regarded as unfolding entities constructed by scientists with various representational means, in which the epistemic purposes and various other ingredients are incorporated. These aspects of a model will not reveal themselves to non-experts, yet without them the model can not be understood, let alone used. Consequently, a model should not be reduced either to the model description or to the imaginary entity that is set up by this description but rather involves both of them. What creates the two and mediates between them is the human activity of modelling. Such other aspects that are built-into models in the process of modelling are: (1) the idealizations, abstractions and simplifications that make the real target system intelligible and workable, (2) the (theoretical) phenomenon into which the original problem was translated, (3) the particular representational forms with the help of which the imaginary (or hypothetical) target system is represented, (4) the experiential and theoretical knowledge used in its development and justification, (5) the new concepts and principles that may emerge in its development, and (6) the relevant observable or measurable parameters of the real target system which link the scientific model to the real target system. With our analysis of the Carnot model we aim to show that it reduces to neither a diagram nor a theory or an imaginary entity, but consists of diverse aspects that scientists have built into it in the process of modelling. 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 function as epistemic tools.

Furthermore, from the perspective on models sketched above, models can be approached as historically evolving entities: what the model consists of, how its content is represented, and how the model can be used in generating knowledge, also developed over the course of time. In a representational view, this change of content of the model is problematic because *the* Carnot model would not have a clear referent. In a pragmatic view, this change of content is unproblematic. The Carnot model “keeps this content together” and what remains stable in its development is (1) the theoretical interpretation of the heat-engine and (2) the epistemic purpose of finding the theoretical limits of the performance of heat-engines.

From the philosophical point of view, a seeming problem of the pragmatic approach is in explaining how models give us knowledge if not by means of a predetermined representational relation with the 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 (as presented in Section 2.2) makes it intelligible how models are justified and how they give us knowledge. The key to this question lies in the activity of modelling. As models are purposefully designed things, they allow scientists to interact with them, which is afforded and limited by the representational means they make use of (which thus determine partly what can be done with the model and what not; examples of representational means are text, pictures, diagrams, graphs, tables, mathematical equations, computer simulations). What is more, we aim to show that scientific models are not only epistemic tools for the purposes of scientific reasoning, theory construction or design of other artifacts and instruments — models also function as *epistemic tools of their own making.* Scientists develop a model step-by-step, buiding in new aspects by which the content of the model becomes richer and more advanced. As an epistemic tool it 'affords and limits' also its own further development, which explains why part of the justification of a model is 'built-in': the development and justification of a model typically concur as already accepted pieces of knowledge and the conventional ways of representing them are incorporated into the model.

It is important to keep in mind, however, that 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. A case can be made that the theoretical activity had taken the form of modelling towards the end of the twentieth century, modelling itself bearing "a distinctive historical signature" (as Peter Godfrey-Smith, [2006, 726]). Certainly, the theoretical strategy of the engineering sciences consists of modelling. Last but not least, since our aims are philosophical, our analysis is essentially reconstructive in aiming to highlight how the *development* and *use* of models can give us knowledge. Although we will present historical facts, we do *not* strive to present a historical account of how Carnot and his successors *actually* developed the Carnot model.

3.2 Epistemic purpose of the Carnot model

The French physicist and engineer Sadi Carnot, in his *Reflexions on the Motive Power of Fire* [1824/1986], gave the first successful theoretical account of heat-engines, which we will refer to as 'the Carnot model of the heat-engine'. Carnot opens his *Reflexions* with the statement: "It is generally known that heat can be the cause of motion and that it possesses great motive power. The steam engine in widespread use today are visible proof of this" (p. 61) He credits English engineers such as Savery, Newcomen, Smeathon and Watt for the discovery, development and improvement of the heat-engine (p. 63). Figure 1 presents a picture of the *mechanical principles* of one of the earliest steam engines, the Newcomen steam engine, invented in 1712 by Thomas Newcomen.

According to Carnot: "The study of these engines is of the utmost interest [because] their importance is immense, and their use is increasing daily" (*ibid.* p. 61) He then states the problem and why a theory of its operation is needed:

> In spite of the many advances that have been made with the heat-engine, and the satisfactory state in which it exists today, the theory of its operation is rudimentary, and attempts to improve its performance are still made in an almost haphazard way.

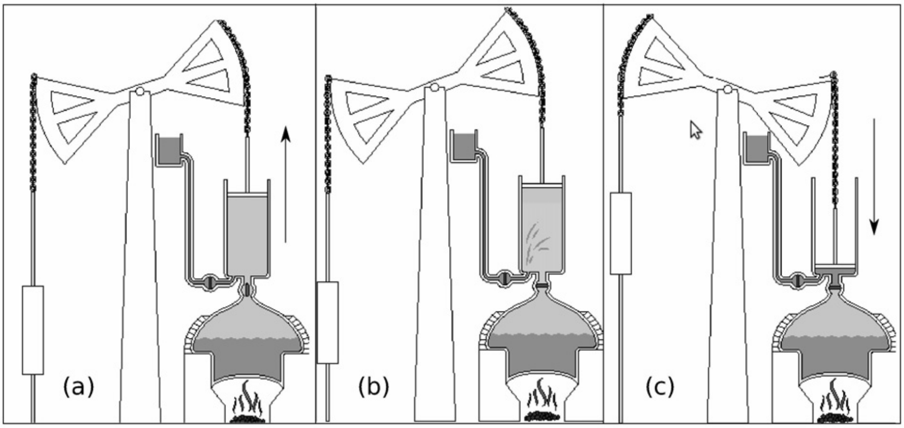

Figure 1. Schematic Newcomen steam engine that presents its mechanical principles. Steam is light-grey and water is dark-grey. Valves between boiler and condenser (the cylinder) move from open to closed. This schema presents three different moments of a cycle. (a) Valve between boiler and cylinder is open. Steam from boiler enters the cylinder and pushes piston upwards. (b) Piston has arrived at its highest position. Valve between cylinder and boiler is closed. Valve between cold sink and cylinder opens and water from a reservoir of cold water sprays in the cylinder causing condensation of steam in the cylinder. (c) Both valves are closed. Piston moves down, which is due to its own weight and the reduced pressure of steam in the cylinder. At the lowest position the valve between boiler and cylinder opens. Water runs back to boiler. Cycle repeats. Figure taken from http://en/wikipedia.org/wiki/Newcomen_ steam_ engine.

> 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? For a long time there have also been attempts to discover whether there might be working substances preferable to steam for the development of the motive power of fire; and that is a question still debated today. Might air, for example, have great advantages in this respect? In the following pages, we propose to examine these questions carefully. (*ibid.* p. 63)

This introduction by Carnot to his theoretical work illustrates that, unlike many of the 'basic' sciences, the engineering sciences usually start from questions related to practical problems and applications, for instance, the problem of how the functioning of a device can be improved. One of the technological problems of steam engines in the early nineteenth century was how to improve their performance, which meant how to reduce the quantity of coal needed for producing an amount of motive power. This so-called duty (now called 'efficiency') of steam engines was expressed as the pounds of water that were pumped to one foot height per bushel of coal. Engineers wanted to know whether the performance of steam engines could be improved by the use of steam at a higher pressure and/or by replacing steam by other vapours or gases. Carnot translated the practical problem of how to improve the performance of these engines to a theoretical question about the limits to the performance of the heat-engine determined 'by the very nature of the things'.

Generally, the first step in developing a scientific model of a device 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 such as represented in Figure 1, but as a device that produces motion by heat.

The phenomenon of interest produced by the heat-engine, according to Carnot, is "the production of motion by heat". This conception of the phenomenon of interest is already part of the development of the scientific model because this phenomenon is not simply observed but discerned or conceptualized by scientists. As a consequence, the description of the phenomenon cannot be easily understood as a representation that stands in a correspondence or similarity relation with the real target system (e.g. the steam engine). Rather, it presents a particular way of 'seeing' or 'imagining' the real device. In Carnot's writings, many other examples can be found of conceptions of phenomena that he discerns and that function as epistemic tools to the development of the scientific model rather than being claims about phenomena that exist or could be observed somehow in the real heat-engine. Examples are: the phenomenon that 'a difference in the temperature of two bodies A and B *brings about* motive power'; and the phenomenon that 'a transfer of caloric from A to B *brings about* motive power'. A scientist who postulates a phenomenon is not obliged to believe that it exists as a real (ontological) occurrence that could be observed had we better instruments. Instead, a scientist must have reasons to believe that the model can be used as an epistemic tool in reasoning about the real target system, in particular with regard to the epistemic purpose of the model.

In brief, producing the preliminary Carnot model requires conceiving of the real heat-engine in view of the epistemic purpose of the model. Imagining it that way involves relevant empirical and theoretical knowledge that allow making abstractions and conceptualizing particular features of the real target system in view of the epistemic purpose. This first modelling step results in a preliminary Carnot model that consists of the conception of the real heat-engine as an abstract device that produces motion by heat. Clearly, the model is not yet satisfactory since it does not sufficiently explain the theoretical limits of the performance of this device. Nevertheless, the preliminary model of the real heat-engine must be such that it allows (i.e. affords and limits) further development of the Carnot model.

3.3 Modelling a hypothetical device

The development of the Carnot model of the heat-engine proceeds by fleshing out the abstract device that produces motion by heat in terms of a preliminary model. In *Reflexions*, Carnot pictures a hypothetical device that produces the phenomenon of interest, i.e. "motion by heat". The hypothetical device consists of a cylindrical vessel closed with a movable piston that encloses a constant amount of gas; this gas can be either thermally isolated, or contacted with a body at a constant high temperature that acts as a heat source, or with a body at a constant low temperature that acts as heat sink. This device produces motion by heat because it goes through a specific cycle by which the piston moves up and down. Carnot describes the working of this hypothetical device as follows, making use of the diagram in Figure 2:

> Let us *picture* an elastic fluid, air for example, enclosed in the cylindrical vessel *abcd* in Figure 3 [see Figure 2 below]. In this figure, *cd* is a movable diaphragm or piston fitted inside the cylinder, and the two bodies A and B are each maintained at a constant temperature, that of A being higher that that of B. Let us now *imagine* the following sequence of operations:
>
> (1) The body A is placed in contact with the air enclosed in the volume *abcd*, ... As a result of this contact, the air assumes the temperature of the body A. At this point, *cd* marks the actual position of the piston.
>
> (2) The piston rises gradually to the position *ef*. Contact between the body A and the air is maintained throughout, so that the temperature of the air remains unchanged during the expansion. The body A provides the caloric that is needed in order to keep the temperature constant.
>
> (3) 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*.

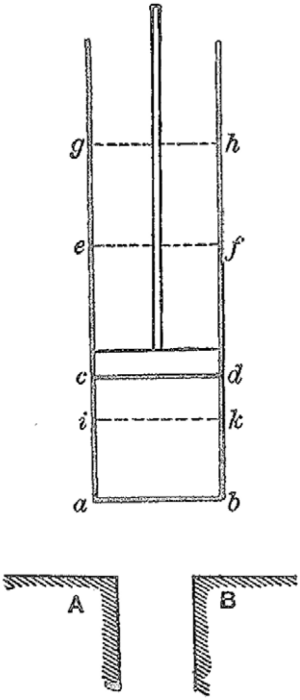

Figure 2. Axial cross section of the hypothetical device, which is part of the Carnot model of the heat-engine. In this diagram, *abcd* is a cylindrical vessel, *cd* is a movable piston, and *A* and *B* are constant–temperature bodies. The vessel may be placed in contact with either body or removed from both (as it is here). Figure taken from [Carnot, 1824, p. 17].

> (4) 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.
>
> (5) 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*.
>
> (6) The air is placed once again in contact with the body A, and the piston returns from *ik* to *ef*; the temperature remains constant.
>
> (7) The third of the stages just described is repeated, followed by stages 4, 5, 6, 3, 4, 5, 6, 3, 4, 5, and so on." (*ibid.* p. 74-75, our italics)

Hence, Carnot developed the preliminary model by building in this more extended conception of a device that that produces motion by heat. In modern language, the successive stages in operating the device are called a thermodynamic or Carnot cycle. Once the cycle is 'running', operation (6) replaces (1) and (2), therefore, the cycle actually consists of four operations: 3, 4, 5, 6. Accordingly, the hypothetical device produces a thermodynamic phenomenon (as we now call it), which is "the production of motion by heat".

3.4 Representational versus pragmatic views on models.

Carnot's conception of (the operation of) a hypothetical device that produces motion by heat, also entails several other aspects. Firstly, it explains how operations with this hypothetical device (such as placing the air in contact with body A or B, or compressing the air in the cylinder) produce observable and measurable phenomena (such as changes in temperature, pressure and volume of the air in the cylinder). This is how the Carnot model gives knowledge of observable and measurable parameters. As a consequence, the Carnot model is connected with the real world target system by means of observable and measurable parameters entailed by the model, whereas a representational view of models would attribute this connection to a representational relation between the model and the real heat-engine as it is in itself — which, with the model in its given state, is hard to imagine.

Secondly, the model entails imaginary phenomena that could not possibly be observed or measured (such as transfer of caloric). Such descriptions of imaginary phenomena in the model could not be justified as part of the model if their justification depended on a representational relation with observable or measurable occurrences. From the pragmatic perspective, positing imaginary phenomena is justified if it enables further reasoning, as long as it does not generate contradictions. Indeed, the conception of 'transfer of caloric' was later rejected, but not because it was somehow discovered that caloric did not exist, but because reasoning upon it led to contradictions.

Also, it is obvious that the Carnot model — which, next to the hypothetical device (operations 3, 4, 5, 6) includes a diagram of this device (Figure 2) — does not represent the mechanical working of the real heat-engine as described and pictured in Figure 1. Moreover, Carnot's conception intentionally neglects all possible losses of energy in a real heat-engine due to the mechanical working thereof, such as loss by friction of the moving piston, loss of steam past the piston, and loss of heat by conduction between parts of the engine at different temperatures. Carnot assumed that these losses should be neglected in order to arrive at a model that explains a limit to the performance of heat-engines which, by the very nature of the things, cannot be surpassed. Hence, the epistemic purpose of the Carnot model justified the neglect of the mechanical workings and related shortcomings of the real heat-engine.

Finally, in modern accounts of the Carnot model, the hypothetical device that produces motion by heat is often called the *ideal heat-engine*. These accounts usually embrace the idea that the Carnot model *is* the ideal heat-engine, which leads us to consider models as abstract entities (for models as abstract entities, see [Giere, 1999]). However, this seems to aggravate the philosophical problem of representation: How are we supposed to relate an imaginary entity to a real target system? Especially as the representational view remains silent about the actual means of representation. Conceiving models as epistemic tools pays explicit attention to the use of external representational means, attributing to this dimension of modelling part of its epistemic value. When it is realized that models are used for making inferences and reasoning, the urgency of grounding the epistemic value of models to a supposed representational relation between the model and some external target system (or its rendering in terms of a data model) vanishes. Instead, the results of a model and its behaviour are related to measurements, experimental results and other existing theoretical knowledge in a subtle process of triangulation.

From the pragmatic perspective modelling proceeds certainly by *representing*, i.e. using representational means for conveying and creating meaning, yet this need not establish any determinable, representational relationship between some real system (or its rendering) and the hypothetical system thus introduced. Thus, when modelling involves the construction of an imaginary object, one does not have to assume that for it to afford us knowledge it would need to replicate accurately some aspects of some real target systems. The epistemic value of modelling is accounted for by referring to the tool-like characteristics of models rather than referring to any supposed representational relationships. In sum, even though models are constructed by making use of representational means, they need not be conceived of as *representations of* any definite real target systems. However, as argued above, the pragmatist analyses of representation show that invoking representation does not per se establish much as regards the epistemic (or cognitive) value of models.

In the preceding sections we took the Carnot model of the heat-engine as our practical example whereby we aimed to argue and illustrate that the pragmatic approach leads to a more intelligible account of modelling in the engineering sciences than the representational paradigm. The remainder of Section 3 aims at reconstructing in more detail how the Carnot model of the heat engine was developed, and, in particular, how Carnot and his successors built, step-by-step, various aspects into their model such as experiential and theoretical knowledge, theoretical principles and concepts, and using new representational means, by which process the model was also partly justified. Furthermore, we aim to answer why and how modelling in this case, which apparently proceeds via detour of a hypothetical device far removed from actual heat engines, nevertheless affords us knowledge about them. In Sections 3.5 and 3.6, we will first illustrate that the development of the model of the heat-engine by Carnot and his successors also proceeded in tandem with the development of the representational means and theoretical concepts used.

3.5 Representational means for developing the Carnot model

An important aspect of developing scientific models is the representational means scientists have at their disposal. Representational means provide the material embodiment of the model that provides its spatial and temporal cohesion that scientists can work on.

From Carnot's *Reflexions*, it becomes obvious that Carnot's representational means were limited. The use of diagrammatic and mathematical representations as we know them today would have made his laborious reasoning much easier for him, and more accessible to the reader. Carnot only used text, a few equations and calculations, and some tables with experimental data and calculations from formula. The only type of diagram he presented is Figure 2. Only Carnot's successors developed several representational means that allowed re-formulation and further development of the Carnot model into the form as we know it today.

Figure 3, for instance, is a modern *block-diagram* of the phenomenon (i.e. the production of motion by heat). This modern diagram represents the heat-engine as a device that converts heat to mechanical work, where heat, Q, flows from a furnace (e.g. a boiler) at high temperature T_H through the fluid of the "working body" (e.g. steam or air) and into the cold sink (e.g. a condenser) at T_C, thus forcing the working substance to do mechanical work, W, on the surroundings, via cycles of compressions and expansions of the fluid. It is striking that Carnot neither used symbols (H and Q) in the representation of the phenomenon nor arrows for representing the directions of work and heat between bodies.

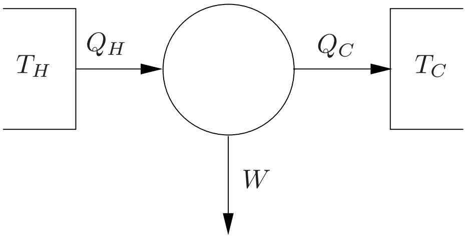

Figure 3. A modern diagram of the Carnot engine, which presents the production of work by heat. In a modern conception, Carnot's ideal heat-engine produces work, W, by heat, Q, by means of a thermodynamic cycle of a gas contacted with a hot reservoir at temperature T_H, and a cold reservoir at temperature T_C. This cycle is now called the Carnot cycle (see also Figure 4). Figure is an adaptation of http://en.wikipedia.org/wiki/Carnot_ heat_ engine.

Similar to Figure 3, the top diagram in Figure 4 shows a modern representational means for representing the 'operation' of the ideal heat-engine, which expands on Carnot's diagram (Figure 2). The pictures (1), (2), (3), (4) in this block-diagram represents the working of the ideal heat-engine, i.e. the four 'operations' 6, 3, 4, 5, respectively, described by Carnot (i.e. the four stages of a — thermodynamic

— cycle of the gas in a cylinder under a freely moving piston). Here also Carnot's presentation is enriched with the use of arrows (while it could have been enriched with the use of symbols Q and W as well): upward and downward arrows inside the cylinder depict heat that flows in and out of the cylinder, respectively, while upward and downward arrows outside the cylinder depict work exerted by, and on the piston, respectively.

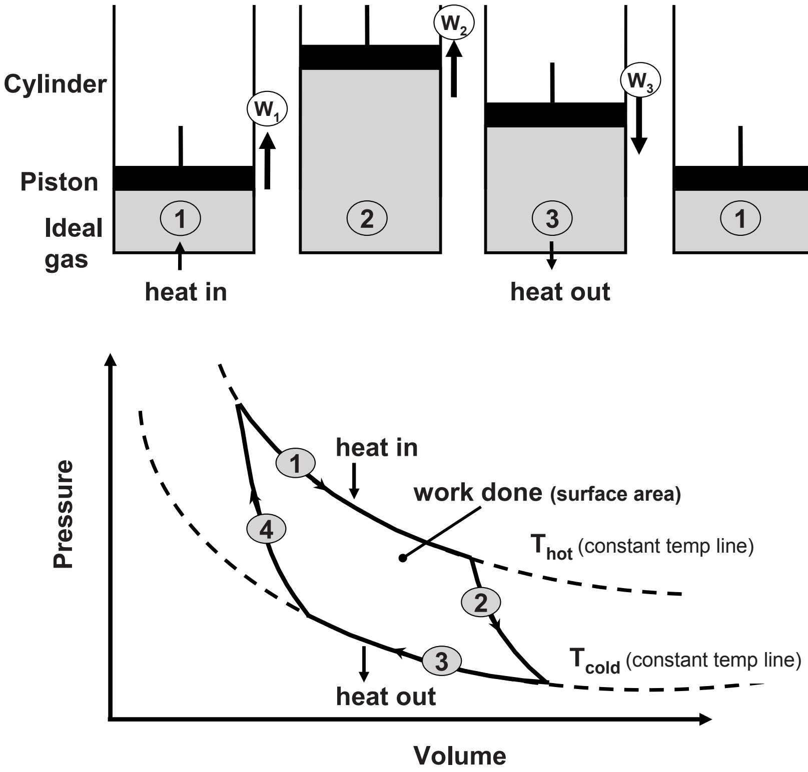

Figure 4. A modern diagram of the hypothetical device that produces motion from heat. The *top diagram* presents the 'operation' of the device, which is a cylinder filled with a constant amount of gas (dark-grey) and closed with a movable piston. The pictures in this diagram, numbered (1), (2), (3), (4) represent respectively the four 'operations' 6, 3, 4 and 5 described by Carnot [1824/1986, 74-75]. The *lower diagram* presents the P-V diagram of the Carnot cycle.

Another important type of diagram that became part of the Carnot model only after Carnot had published his *Reflexions*, was invented by Benoît Paul Émile Clapeyron, likewise a French engineer and physicist, who, ten years later, presented the cycle as a closed curve in a graph of the pressure P of the gas in the cylinder against its volume V. At present, this graph, of which a version is presented in the lower diagram of Figure 4, is called a *P-V diagram of the Carnot cycle*. Additionally, modern conceptions of the ideal heat-engine expand on Carnot's description of the cycle, i.e. the 'operations' described in 6,3,4,5 by introducing new thermodynamic concepts, such as 'reversible isothermal expansion', that were only developed by Carnot's successors. These new concepts allowed for a more efficient and precise description of the Carnot cycle.[4]

Finally, new mathematical approaches became part of the Carnot model through the work of Rudolf Julius Emanuel Clausius, a German physicist and mathematician, who in 1865 published *The Mechanical Theory of Heat — with its Applications to the Steam Engine and to Physical Properties of Bodies.* Besides other things, he developed a model of the conversion of heat, Q, to work, W, by using *differential calculus* as a representational means for representing the Carnot cycle. This new representational means allowed, for instance, to mathematically describe *reversible* processes. In the first chapter (*Mathematical Introduction*), Clausius explains the mathematical apparatus. In subsequent chapters he develops the 'mechanical theory of heat' by using this apparatus for constructing mathematical equations that represent, for instance, the Carnot cycle. Hence, the cycle of the gas in the heat-engine proposed by Carnot was represented in a completely new way, and the resulting mathematical model affords and confines particular new ways of reasoning and manipulating with the model. Such inventions of representational means did not only improve the understanding but also played an indispensable role in the further development of the Carnot model to ever clearer and richer models of heat-engines by his successors.

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[4] Today, the Carnot-cycle is for instance described as follows (the numbers 1, 2, 3, 4 in this description refer to the numbers in the two diagrams in Figure 4):

1. (= Carnot's operation 6) *Reversible isothermal expansion of the gas at the "hot" temperature*, T_H (i.e. isothermal heat addition). The gas expansion is propelled by absorption of heat Q_1 from the high temperature reservoir. During this step the expanding gas causes the piston to do work W_1 on the surroundings.

2. (= Carnot's operation 3) *Reversible adiabatic (i.e. isentropic) expansion of the gas* (i.e. no heat is transferred to or from the gas in the cylinder: Q_2=0). In this step the piston and cylinder are thermally insulated, so that no heat is gained or lost. The gas continues to expand, doing work W_2 on the surroundings. The gas expansion causes it to cool to the "cold" temperature, T_C.

3. (= Carnot's operation 4) *Reversible isothermal compression of the gas at the "cold" temperature*, T_C (i.e. isothermal heat rejection). During this step the surroundings do work W_3on the gas, causing heat Q3 to flow out of the gas to the low temperature reservoir.

4. (= Carnot's operation 5) *Reversible adiabatic (i.e. isentropic) compression of the gas* (i.e. no heat is transferred to or from the gas in the cylinder: Q_4=0). The piston and cylinder are thermally insulated. During this step the surroundings do work W_4on the gas, compressing it and causing the temperature to rise to T_H. At this point the gas is in the same state as at the start of this cycle.

3.6 Theoretical knowledge and concepts for developing the Carnot model

In order to understand Carnot's way of reasoning in developing the model, we also must master some of the theoretical and experimental knowledge he was familiar with, as well as concepts that were unknown to him while familiar to us. An outline is presented only in as far as it helps to illustrate how knowledge at the time (and the lack of it) is part of how the model is developed; by no means does it aim to present a complete outline.

Important is the conception of heat. In Carnot's time, the prevalent theory of heat was the caloric theory which supposed that heat was a sort of weightless, invisible fluid that flowed from hotter to colder bodies. It was also assumed that caloric is a substance, which, like matter, is indestructible. Only by the mid-19th century was the caloric theory replaced by a theory of heat (using the notion 'quantity of heat', referred to as Q) by the work of scientists such as Clausius, James Joule, William Thomson (Lord Kelvin), and James Clerk Maxwell. Clausius and Thomson rejected the idea that heat is a substance (i.e. caloric), because it led to contradictions in the Carnot model. Clausius explains: "Heat is not invariable in quantity; but ... when mechanical work is produced by heat, heat must be consumed, and that, on the contrary by the expenditure of work a corresponding quantity of heat can be produced." Therefore, in the new *mechanical theory of heat*, the nature of heat is "not a substance but a motion". Clausius argues that "According to this theory, the causal relation involved in the process of the production of work by heat is quite different from that which Carnot assumed. Mechanical work ensues from the conversion of existing heat into work, just in the same manners as, by the ordinary laws of mechanics, force is overcome, and work thereby produced" [Clausius, 1865, p. 268]. Hence, whereas Carnot believed that work is produced by the *fall* of a quantity of heat from a higher to a lower temperature, the mechanical theory of heat argues that work is produced by motion.

A brief intermezzo about this change of the theory of heat can illustrate somewhat further why it is important to understand scientific models in terms of how scientists interpret and structure what they observe or experience (cf. Boon, forthcoming). Carnot and his predecessors interpreted heat as a substance. Adopting the idea that heat is a substance means that one 'imagines' heat as an indestructible thing. Subsequently, they used this conception of heat in their further reasoning and modelling. Carnot thus imagined heat as a fluid that can be carried from one body to another (where it is carried by other fluids such as steam), without being consumed or produced. Replacing this conception of heat by the idea that heat is motion that acts as a force is a tremendous intellectual achievement. Obviously, Clausius and other successors of Carnot did not *observe* that heat actually appears *not* to be a substance but a motion; instead, they found that this conception of heat leads to contradictions, which forced them to find a new conception.

In developing the model also experiential and theoretical knowledge was built in. Carnot was familiar with the gas-laws of Boyle-Marriote (which states that at constant temperature, the absolute pressure and the volume of gas are inversely proportional), the Charles law (which states that at constant pressure, the volume of a given amount of gas and the temperature in Kelvin are proportional), Gay-Lussac's law (which states that the pressure of a fixed amount of gas at a fixed volume is proportional to its temperature in Kelvin), and Dalton's law (which states that the total pressure exerted by a gaseous mixture is equal to the sum of the partial pressures of each individual component in a gas mixture). See [Carnot, 1824/1986, p. 78]. The ideal gas law as we know it today, and which includes Avogadro's principle (which asserts that equal volumes of ideal or perfect gases, at the same temperature and pressure, contain the same number of particles, or molecules), was only stated by Clapeyron in 1834 (i.e. after the publication of Carnot's work).[5]

3.7 Why and how the Carnot model of heat-engines yields knowledge

In exploring why and how the Carnot model gives knowledge, we will focus on the question how Carnot arrived at the description of the ideal heat-engine (presented in Section 3.3), which he pictures as a fixed amount of air in a cylinder closed with a piston that performs "a sequence of four operations" 3, 4, 5, 6. In our reconstruction, we will ignore many of Carnot's refined and intelligent arguments;[6] we will also ignore arguments that are grounded on his conception of heat as an indestructible substance (i.e. his use of 'caloric').

Accordingly, our reconstruction of Carnot's modelling returns to the preliminary Carnot model of the heat-engine, which entails the abstract device that produces

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[5] At that time (around 1824), the basic laws of thermodynamics had not been formulated either. Nevertheless, Carnot is often called the father of thermodynamics. Around 1850, Clausius and Thomson formulated the first and the second law of thermodynamics (abandoning the caloric theory), which state (1) the conservation of energy, and (2) that heat cannot of itself pass from a colder to a warmer body (formulated by Clausius [1854, p. 116; 1865, p. 270]); the modern version of the second law reads as follows: the entropy of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium. This notion of entropy was not known to Carnot but developed and named by Clausius, who, besides other things, wanted to understand in a fundamental way why "heat cannot of itself pass from a colder to a warmer body". He introduced this concept in order to account for the heat-loss when "heat of one temperature is transformed in the heat of another temperature" (ibid p.217, and p. 357). The entropy, S, of a body is the ratio between heat, Q, and temperature, T, while the change of entropy is the dissipative energy use, or irreversible heat loss, during a change of state:

$$\Delta S = Q\left(\frac{1}{T_2} - \frac{1}{T_1}\right).$$

[6] For instance, arguments for the theorem that the magnitude of the work produced is "independent of the nature of the substances through which the production of work and the transfer of heat are effected." Carnot's proof of the necessity of such a relation is based on the axiom that it is impossible to create a moving force out of nothing, or in other words, that perpetual motion is impossible. (cf. [Carnot, 1824/1986, pp. 69-70; Clausius, 1865, p 268]).

motion by heat and the epistemic purpose of the modelling (i.e. identifying the theoretical limits of the performance of the heat-engine). Carnot carried on with the modelling by using this abstract device and theoretical knowledge of heat (caloric) for interpreting the working of a 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)

This interpretation explains how in a steam engine heat (caloric) is transported. In this way, the abstract device that produces motion from heat has become more substantial. Carnot concludes that the steam simply serves as a means of transporting the caloric (heat), and that "the production of motive power in a steam engine is due not to an actual consumption of caloric *but to its passage from a hot body to a cold one*" (*ibid.* 65).

Clearly, the modelling just described did not primarily aim at a faithful representation of the mechanical working of real heat-engine. Moreover, not much can be *deduced* from the Carnot model at this point. This is one of the reasons for regarding scientific models as 'epistemic tools' rather than representations. Tools afford but also confine what can be done with them without deductively determining the result since this result also depends on aspects built in by the cognitive agent (see above). How this is done, in turn, depends on epistemic purposes and specific background knowledge of cognitive agents. Accordingly, the modelling aims at producing an epistemic tool that affords reasoning about the production of motion by heat in an ideal heat-engine.

Carnot proceeded in his modelling endeavour by introducing propositions and principles that relate the transport of heat (caloric) and the production of motive power to other relevant parameters such as temperature, volume, and compression or expansion of the gas in the modelled steam engine. His development of propositions and principles is reconstructed and summarized in the list below (*ibid.* pp. 64-67, selecting, paraphrasing and numbering of principles by the authors):

a) An experiential principle is that equilibrium restores wherever a difference in temperature exists, which means that

b) heat (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,

c) in steam engines motive power is produced by the re-establishment of the equilibrium of caloric, not by consumption of caloric, and

d) whenever there is a difference in temperature, motive power can be produced. while the converse is also true, that is,

e) 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.

f) The heat-engine is any engine that is driven by caloric.

g) It is an experimental fact that the temperature of gaseous substances rises when they are compressed, and falls when they are expanded.

h) An obvious principle is that heat can only be a source of motion in so far as it causes substances to undergo changes in volume or shape.

Next, these principles guide Carnot in abstracting 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 (caloric). 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. Subsequently, he reinterprets his conception of the working of the steam engine represented in the model in terms of relevant parameters (e.g. temperature, pressure, volume, caloric, expansion and compression of the steam) and in terms of three distinct operations. This results in the following reinterpretation of his former description of the steam engine (*ibid.* pp. 67-68):

> 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.

In turn, this developed conception of the steam engine allows further modelling. Here, Carnot makes use of a (preliminary, non-mathematical) notion of 'reversible' processes by which he assume that operations (such as i, ii, iii) can also be carried out in the opposite direction. Based on this notion of reversibility, he 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 steam in the cylinder can brought back to its initial state in order to achieve a closed cycle.[7]

The introduction of new principles is another aspect of how scientific reasoning by means of models yields knowledge. In Carnot's modelling this worked as follows. In his description of operations i, ii, and iii Carnot develops a picture that is close to experience (since he used experiential knowledge of how a steam engine works). Subsequently, by introducing the principle that "there is no reason why a process could not be reversed", he connects knowledge from experience with a completely new principle. This approach results in a description of processes that may not yet be part of one's experiences; nevertheless, one may believe that they could be brought about by a device. This way of scientific reasoning yields knowledge, not because this process was somehow observed and the description thus represents something external to us, nor because it was deduced from the model or from accepted theories, but because Carnot was able to relate the model at that stage with his conception of reversible processes.

At this point, Carnot has developed a model of the heat-engine that goes through a cycle (i, ii, iii, and reverse), but he still needs to find out *how this cycle will produce the maximum amount of motive power.* With regard to how heat produces motive power, Carnot introduced principle *h*. By introducing some additional propositions and principles, he explains losses (and avoidance of losses) in the production of motive power by heat. Carnot's development of these propositions and principles is reconstructed and summarized in the list below, which proceeds from principle *h* in the former list (*ibid.* pp. 66-73, selecting, paraphrasing and numbering of principles by the authors).

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:

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[7] Interestingly, by introducing this notion of reversible processes, Carnot also introduces the working of a heat pump (a refrigerator), which is a device that transfers heat from a cooler system to a warmer one by compressing the gas (by exerting an external force).

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.

According to Carnot, some of these principles are 'obvious' (e.g. *h*), whereas others are derived by logical reasoning about the theory of heat (e.g. *j*). Principle *k* presents a necessary condition for producing the maximum amount of motive force.

At this point, the Carnot model consists of the description of how the steam engine works in terms of a cycle (i, ii, iii and reverse), the epistemic purpose of how this cycle will produce the maximum amount of motive power, and theoretical and empirical principles such as $a-l$. Again, further modelling proceeds from this model, that is, the model functions again as an epistemic tool in its own further development. From principles $h-l$, Carnot infers that the cycle avoids any "change in temperature that is not due to a change in volume". By using principles $h-l$, he signifies where the problem of achieving the maximum effect lies: If a gas is rapidly compressed, its temperature rises (as stated in *l*). If we wish to bring this gas back to its original temperature without subjecting it to any further changes in volume, we must withdraw some caloric from it (*ibid.* p. 74). Hence, the problem is that the gas is brought back to its original temperature while keeping it at constant volume, which, according to principle *j*, means that "caloric is restored profitlessly". The model in its current state guides Carnot in constructing an operation that overcomes this problem. Accordingly, he argues that it would be equally possible to withdraw the same caloric during the process of compression in such a way that the temperature of the gas would remain constant. The rise of temperature that would be due to rapid compression is thus avoided. By this solution, Carnot has constructed 'operation' (4) of the cycle 3, 4, 5, 6 (described in Section 3.3):

4. The air at T_B is placed in contact with the body B; it is then compressed while withdrawing caloric, attaining a decrease in V while T remains constant.

It should be noted that this operation could not possibly be derived from mere experience with real steam engines.

Likewise, if the gas is rapidly expanded (by which, according to principle *l*, the temperature would fall), the fall of its temperature can be prevented if we supply to it an appropriate quantity of caloric. Carnot has thus constructed 'operation' (6) of the cycle 3, 4, 5, 6:

6. The air at T_A is placed in contact with the body A; next, the gas expands while supplying caloric, attaining an increase in the volume while the temperature remains constant.

From what is given in the model at this point, i.e. by making use of the cycle (i, ii, iii and reverse) and the given principles, ‘operation’ 3 and 5 can be constructed as well:

3. Body A is removed. The gas expands while it is no longer in contact with any body that can act as a source of caloric. Hence, there is a simultaneous increase in the volume of the gas and fall of temperature until it is equal to that of body B.

While ‘operation’ (5) is the reverse process:

5. Body B is removed. The gas is compressed, while it is no longer in contact with any body that can withdraw caloric. There is a simultaneous decrease in the volume of the gas and increase in temperature until it is equal to that of body A.

At this point, the Carnot model consists of the description of cycle 3, 4, 5, 6 and the theoretical and empirical knowledge represented in $a - l$. This model meets the epistemic purpose of telling how this cycle will produce the maximum amount of motive power. The model can be used as an epistemic tool in producing knowledge about the behaviour of the real target system (the real steam-engine) because in modelling the hypothetical device (e.g. gas enclosed in a cylinder with a movable piston, and body A and B that represented furnace and cooler) was related to the description of the real steam engine (e.g. boiler, condenser, cooling water and furnace) and to observable occurrences and measurable quantities (such as changes of volume and temperature of a fluid). The model is not a representation of real heat engines. Instead, the knowledge about the real device obtained from this model is confined to its epistemic purpose and thus allows for inferring from it some suggestions as regards the construction of real steam engines. Carnot, for instance, suggested that principles j and k “must constantly be borne in mind in the construction of steam engines. If the principle cannot be strictly observed, any departure from it must be reduced to a minimum.” (*ibid.* p. 70). Additionally, the Carnot model at this point was used by his successors. They used this model as an epistemic tool in its further development. As was already mentioned, they have built in new representational means such as the differential calculus by which a more refined understanding of the ideal heat-engine was developed, as well as a mathematical description that afforded further development of the Carnot model (and which allowed making calculations such as the maximum theoretical efficiency). Carnot’s successors also used his model in the development of thermodynamics (see footnote 9).

3.8 Model construction and model-based reasoning

We have illustrated how Carnot developed his model of the ideal heat-engine, and how at different stages the model guided its own further development. At these stages, the model at that point in the process of modelling was used as an epistemic tool for taking the next modelling step. Strikingly, one can discern a succession of different ways in which the model enabled its own making, thereby also guiding the incorporation of new aspects which will be summarized below.

The modelling starts from specifying an intended *epistemic function* that the model of a device or material has to fulfil, such as finding the theoretical maximum efficiency of heat-engines. Second, in the light of this epistemic function, a *phenomenon* is identified and conceptualized in terms of which the proper functioning of the device or material can be understood (e.g. the phenomenon of producing work by heat in heat-engines). Third, an *idealized device* or idealized *material* that produces the phenomenon of interest is conceptualized. This conception *abstracts* from several features of the real device or the real material (e.g. from the mechanical working of the real heat-engine) in view of the epistemic purpose. Fourth, the functioning of the idealized device or material is conceptualized in terms of 'operations' or physical processes, implying that *knowledge of the relevant 'operations', physical processes, phenomena or properties is built into* the model (e.g. knowledge of physical processes relevant for describing heat flows and the exertion of work that results from exposing the idealized device to certain external conditions was incorporated). Fifth, principles (e.g. how the maximum effect is achieved) and theoretical knowledge (e.g. the gas laws of Boyle, Mariotte and Gay-Lussac) about these 'operations' and physical processes in terms of physical variables relevant to the device or material (e.g. P, V, T, and specific heat) are incorporated in the model. Also, *experiential principles* (e.g. tendency to equilibrium of temperature) were incorporated in the model. Consequently, looking at the Carnot model from the perspective of its construction makes it plausible that the very activity of developing the model (i.e. modelling) guided Carnot in finding the thermodynamic cycle that produces the theoretical maximum efficiency of an ideal heat-engine.

We suggest that these different ways of incorporating successive aspects into the model are not particular for the Carnot case, but instead present a more general account of modelling processes in the engineering sciences. We do not claim, though, that we have covered all relevant aspects, nor that all aspects mentioned can be found in every model. Our analysis of this case is at odds with those widely held views on models (stemming from the syntactic view of theories), which assume that models are derived from theories or general principles. Indeed, in modern textbooks, the Carnot engine is usually presented as if it were somehow derived from thermodynamic theory. However, historically it was the Carnot model of the heat-engine that contributed to the theory of thermodynamics and only in retrospect could it be viewed as satisfying the axioms of thermodynamics (cf. [Erlichson, 1999]). With regard to the semantic view of models, we argue that it neglects some crucial questions concerning modelling, particularly how scientists arrive at model systems (such as the ideal heat-engine). In that view, the system model is taken for granted, while we have illustrated that much theoretical work needs to be done in order to arrive at a model system (cf. Hodges, this Volume).

Summing up, the Carnot model of a heat-engine is like many other scientific models in that it depicts an ideal entity that can be interpreted in terms of a phenomenon (that of producing motion by heat), which makes the model prone to further scientific examination and explication. Instead of describing a real object (the real heat-engine) the Carnot model actually presents an ideal object, similar to the model of an ideal pendulum, the Lotka-Volterra predator-prey model, or economic models of ideal economies. Also, the process of developing the model (i.e. modelling) has lead to conceptual novelties: the notion of "the efficiency of turning heat into work" did not exist before Carnot's theoretical model, nor did the idea according to which*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.* The model of the ideal heat-engine incorporated various kinds of experiential and theoretical knowledge (e.g. the gas laws) and as it afforded thinking about the behaviour of heat-engines in a novel way it also led for its part to the consequent development of the thermodynamic theory.

4 TOWARDS AN EXPANDED NOTION OF MODELS

We have argued against the generally accepted idea among philosophers that models can be regarded as representations (variously defined) *of some real target systems.* As an alternative, we have proposed a pragmatic account of models as epistemic tools. We are of course not the first to argue against the representational view of models. Yet, even in those accounts, the notion of representation tends to re-enter the scene when it comes to answering the question why models can be used to knowledge about real target systems. Thus, for instance, after having argued for the importance of building and manipulating models, Morrison and Morgan [1999] claim that we can learn from models because they represent their target systems. We have argued, instead, that conceiving of models as standing in a direct representational relation with some real target systems does not shed light on their epistemic functioning. Philosophically, our proposed notion of models as epistemic tools focuses on the cognitive value of modelling and its different roles in scientific enterprise highlighting the importance of different representational means for model-based reasoning. From the practice point of view, one of the problems of the representational approach is, rather paradoxically, that by concentrating on the relation between the model and its real target system, it abstracts from the actual representational means with which scientists go about building their models.

The representational account of models also leads to problems concerning the ontology of models, which has recently attracted quite a lot of interest in the philosophy of science. The question has been whether scientific models should be conceived in terms of the model descriptions (i.e. pictures, diagrams, or mathematical equations) or whether they are abstract or imaginary entities. From the representational perspective it seems crucial to single out the very entity that is supposed to correspond to the real-world systems. Yet both the alternatives proposed, i.e. models as model descriptions and models as abstract or imaginary entities, lead to trouble. Models cannot be identified with model descriptions because mere descriptions in and of themselves signify nothing. On the other hand, it seems difficult to explain how an abstract or imaginary entity, quite apart from its description, succeeds in enabling any reasoning. As opposed to this perspective, our approach to models as epistemic tools invokes the activity of modelling implying thus an extended notion of models as unfolding entities, which are constructed with concrete representational means conveying a hypothetical content. From this perspective, a model reduces neither to an abstract entity nor to the representational means with which it is constructed. The diverse aspects making an irreducible part of modelling include, for instance, (1) the epistemic purpose(s) the model has to fulfill, (2) the phenomenon that determines the function of the device or material of interest, (3) the abstractions and idealizations needed to construct the hypothetical objects, (4) the different types of the representational means used, such as diagrams, pictures or symbols, (5) physical, theoretical, and experiential knowledge or principles that are built into the model, and (6) relevant physical variables and parameters that are either known, measured, or determined otherwise, and which relate the model with what is observable or measurable by means of instruments. It seems to us that without taking these aspects of modelling into account it would be incomprehensible how scientists were able to develop models and reason with the help of them. Often these aspects go without any explicit notice in scientific practice but this does not license philosophers to neglect them in their accounts of models.

Last but not least, approaching models as epistemic tools leads us to consider the various epistemic uses of models, such as scientific reasoning, prediction, theory construction, concept formation and design of other artefacts, instruments, or experiments. There is no reason to expect that they draw in the same direction and thus scientists use often different and conflicting models even when considering the same phenomenon, depending on the task at hand. However, finding out more about how the diverse tasks of models perhaps reinforce or alternatively contradict one another seems an interesting direction for further research. indexdesign

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