Handout (d.d. December 17, 2014.**) for final assignment Philosophy of Engineering: Science.**

The B&K theory of scientific modelling. A tool for (re-)constructing scientific models.[i]

Mieke Boon.

1. Introduction

[Also see Lecture notes on 'Explanation, Hypothesis & Modelling'!] Scientific models are on paper (they are different from, e.g., an experimental model). They present us with knowledge, such as a description or an explanation of a system (or phenomenon). If you find the word 'phenomenon' difficult to handle, replace it with 'system.'

The aim of the B&K theory is to present you with a method for (re)-constructing scientific models for better reading scientific articles, in particular in fields you are not completely familiar with. Better reading means, more efficient; with more in-depth understanding; and with more insight in whether and how you can utilize the knowledge presented in this article. Furthermore, it is a method for designing (and presenting) your on research proposal (e.g. your MSc project).

Imagine a student who had received a disappointing mark for his MSc research. The error he made was that he had used formulae from the literature just because these formulae had the same parameters as those in his measurements. However, apparently these formulae were inappropriate for his problem. How could he have known this? The student had no clue about how to know whether he could use it or not. That is what this assignment is about: to understand how knowledge is made (how it is 'constructed'), and how to find out whether you can safely use it.

2. Models as 'epistemic tools'

The B&K theory is a method, which, in a way, takes a typical engineering approach in assuming that a scientific model is not a kind of picture of 'how the world is', but instead, a '<u>tool for thinking</u>'.
One of the aims of the PhoSc course is to understand scientific research not first and foremost as an attempt to discover 'true pictures of the world behind the phenomena', but as an attempt to construct '<u>epistemic tools</u>', that is, 'tools' with which we can think about problems in research or engineering, and with which we can produce knowledge and ideas about, e.g., how to solve these problems. An example given in presentation 6 (slides 6) is Carnot's model of the ideal heat engine (and see the article by Boon&Knuuttila), which is a model that explains and predicts the limits of the most efficient heat engine, and tells which variables determine the actual efficiency. So this model is a 'tool for thinking' as it may give ideas on how we can design more efficient heat engines (e.g., steam engines).

In brief, when talking about the engineering sciences, we start from the idea that scientists 'construct' scientific models (of which the construction of Carnot's model of the ideal heat engine has been given as an example), instead of 'true pictures.'

3. The hypothetico-deductive method.

In a common view of science, we tend to think that scientific research aims at true (or empirically adequate) pictures of the world. Common ideas about scientific methodology suits to this view. Recall, for instance, the so-called hypothetical-deductive method (in which, from observations and questions, scientists infer to a hypothesis that aims to explain the observations, etc.). This idea about 'good' scientific methodology' very much suits the 'classical' idea that the aim of science is true pictures of the world 'behind' the observable phenomena (including measured data). When having this 'classical' picture in mind, the structure of a scientific article is: (a) these are my observations; (b) this is the hypothesis that explains them; (c) these are the experiments that I will do to test the hypothesis; (d) these are the results; (e) these results confirm or falsify my hypothesis; (f) conclusion: hypothesis has been confirmed or falsified [although you will hardly find articles in which scientists present a falsification. Instead, they introduce their own hypothesis by claiming that others were wrong – e.g., "we have falsified their hypothesis, and therefore, we propose such and such improvement."]

Note that many scientific articles still have this structure! WARNING REGARDING THE ASSIGNMENT. The assignment is NOT to summarize a scientific article according to the HD structure, even though the article that you analyze may very well have this structure! The point of this assignment is to learn that there are other ways of understanding/analysing the content of a paper. Again, the reason why this is important is to avoid the errors of the mentioned student, but also to become capable of more easily understanding difficult articles, and to become more creative yourself.

Although writing (and reading) a scientific articles along the lines of the HD method is not wrong (and in fact, many articles are indeed structured this way), this structure often is of limited value. Why? Well, think of the way in which you will approach the content of an article. You may think, "If the researcher has done her work well (and we must assume that this is the case when the work has been published in peer reviewed journal), you can simply jump to her conclusion. The rest of the article is of no real interest. You pick the formulae (as this student did), because this formulae has been confirmed by the method." The point is that you CANNOT simply jump to the conclusion of the article and apply it to your own research problem.

Let's turn the Quine-Duhem thesis on its head. What I mean is this. In confirming a hypothesis, many 'auxiliary' aspects play a role. These aspects are described in the article. So, only the **formulae + auxiliary aspects** have been confirmed. Examples of auxiliary aspects are that scientists have made assumptions, simplifications, or worked with highly idealized experimental systems. It is very important to take these into account!
In the classical picture of science, the laws (formulae) have been confirmed by applying the scientific method, and therefore, are *universally* applicable (and the unlucky student had this picture in mind when he made his errors in 'simply' applying it).
In understanding this, you can also recall the problem of induction.

[Hopefully, you will recognize the different topics of the course – and see their relevance.]

4. Discovering versus constructing scientific knowledge.

Recall the examples of Sadi Carnot (in previous years of this course, we also discussed Newton and Maxwell). These great scientists are often seen as people who made crucial discoveries. You all know this popular high-school story: "Newton discovered gravity when he saw a falling apple." By reading their own, original texts you will understand that this is not how it went. Discovering a scientific theory is not like discovering America or the skeleton of a Dinosaur. It is not like opening a black-box and to discover what is in it: "hey look, there sits gravity (or, the Higgs particle); finally I have found it!" Instead, what you have hopefully noticed is that these scientists constructed their theories rather than discovering them. Newton constructed a physico-mathematical model for mathematically describing (and explaining?) moving bodies. Did his model also explain moving bodies? Well, this is a delicate issue. Newton was reluctant and very cautious in calling it an explanation, since, as an *explanation* it involved a metaphysical background picture (action at a distance) that, at the time, was vigorously rejected.
Newton did not discover gravity (gravity was already known). Instead, he constructed a definition (or, a new scientific concept) that (conceptually and mathematically) defines force as that which is responsible for change of the velocity of a mass. His whole treatise can be read as a very carefully thought through construction that aims to be a mathematical (and explanatory?) account of mechanical phenomena in general. [We may say that Newtion' theory of universal graviation is explanatory (in the physical sense) *only* if Newton would have claimed that gravitational force really exists as a physical capacity, but this is where Newton was cautious. Historians of science debate whether Newton did, or did not make this claim.]
This take on scientific papers makes reading them so exciting. Not the conclusion is the most important, but *how* it was constructed! – Which often is brilliant (and from which we, ordinary beings, can learn a lot).
Also Maxwell was busy with constructing a model of the aether that could explain observable phenomena in electricity, magnetism and light. Carnot constructed a model of the ideal heat engine, which is the model of a system that does not even exist in reality.

One of the ideas I aim to get across is that seeing these theories (or models) as discoveries makes us blind for how scientists came up with their hypotheses anyway. Many of you may know the story of how Kekulé discovered the structure of benzene. This story suggests that the structure of benzene was discovered in a dream about a snake. It is a kind of paradigm example of how discoveries are made. Another famous example is Bohr using the analogy of the solar-system in coming up with his model of the hydrogen atom. Of course, coming up with a good explanation often involves moments of creativity or inspiration, for instance, by using analogies. My point is that much more is needed for making a good theory, as we can see from Carnot, Newton and Maxwell. By these examples, we find that a good theory or model largely results from constructing it.

In reading these texts of Newton and Maxwell, you may also have noticed that the HD-account is inappropriate in the following way. The HD account of scientific methodology suggests that scientists come up with a hypothesis (which, when confirmed well enough is the model or theory). Subsequently, this hypothesis is tested by means of experiments, which either confirms or falsifies it. The difficulty of the HD-account is that it doesn't tell us anything about where the hypothesis comes from. As said, the history of science in our text-books often suggests that the hypothesis came from a flash of inspiration. In real scientific practices, however, a lot of constructive activity is involved in constructing a scientific model or theory (again, think of how this goes in the examples). This also implies that much of the justification of the model has been already done in constructing it! Often there is limited testing in experiments. The popular story is that Newton came up with his hypothesis, which was then tested in experiments. But this is not at all how it actually went. Instead, he constructed a theory by putting together, and making use of several elements (definitions, empirical knowledge, principles of philosophizing, mathematical methods, thought-experiments). The same holds for Carnot and Maxwell. In fact, in many cases experiments are only done to measure or fit parameters postulated in the theory (e.g., the gravity constant, or magnetic permeability, or R in PV=nRT) – in these cases, scientists assume that it has been sufficiently proven by how the model was constructed.

5. Intermezzo.

Interestingly, 'fundamental' theories (also called 'axiomatic theories') cannot be proven to be wrong. Newtonian mechanics is, by definition, correct for a specific type of systems – called, 'Newtonian systems' – for which it has been constructed. Einstein came up with systems that were not Newtonian, and constructed a more general theory which can account for both Newtonian and relativistic systems. Next, it is important to recognize that mathematical models of specific types of Newtonian or EM systems are constructed by means of axiomatic theories (think of the examples in your textbooks, where mathematical models for Newtonian or EM systems are constructed by means of axiomatic theories such as Newton's or Maxwell's resp.) are correct in principle. BUT, they are only correct about the ideal system. Scientists fit these models to the real world system, firstly, by fitting out or measuring the parameters in those mathematical models, and secondly, by explaining deviance between the model-outcomes and the outcomes of experimental measurements by means of 'disturbing' physical phenomena that were not included in the model of the 'ideal system' (e.g. 'air-resistance' on the falling object in Newtonian mechanics). The mathematical model is improved by adding these additional aspects, rather than taking such deviances between model predictions and experimental outcomes as falsification of Newton's laws or Maxwell's laws!

Or, take Ohm's law, V=I.R. Can this law be proven wrong? Rather, this law is taken as a definition that relates V, I, R. The law is a definition because R, I and V cannot be measured independently. Hence, in using this law, you must realize that it is true by definition, but that this does not imply that, e.g., R (resistance) is a constant in your actual systems (a wire or a layer or etc.). This is where the importance of measurements and experiments lies! Hopefully you recognize that presenting Ohm's law as resulting from applying the HD-method is a bit too simplistic. Moreover, the HD-picture easily leads us astray in the way you may understand the character of this law. Yes it is universal (as a definition), but the law doesn't tell the truth about the concrete physical system that you are working with (as it does not tell that electrical resistance is a constant).

6. Overview.

From the previous part we may draw several conclusions:

1. The HD-method is limited as an account of how hypothesis are constructed and as an account of how models and theories are justified (i.e., confirmed or falsified).

2. The HD account of scientific methodology is also a bit tricky as it may easily lead you astray. Usually, you have less knowledge in your hands than the idea of ‘universal laws’ suggests. With universal laws, you only have definitions. Ohm’s law is a law that defines the relation between measurable parameters that cannot be measured independent of each other. Therefore, you have to be careful in applying it to real physical systems. It requires measurements and experiment to see, for instance whether the electrical resistance is constant throughout your system. Ohm’s law doesn’t say anything about that.
3. The HD account of scientific methodology does not make clear that much of the justification (confirmation or falsification) has already been done in the construction of it (think of Carnot, Newton, Maxwell). The role of experimentation, often (but not always) is to determine parameters of the model, and to see whether the model is accurate and adequate enough for the kind of systems you aim to use it for. Often, other physical phenomena occur in the actual system. These are ‘discovered’ in our experimental work. So, according to the HD model, disagreement between our mathematical models and measurements of the actual systems would imply that scientists have falsified the mathematical model, but in fact, such findings are used to ‘discover’ other effects and adapt the model.
4. In order to know whether you can use the presented knowledge, you must always carefully look at how it was constructed (and this is what the B&K theory helps you with). You must know for which kinds of systems (or problem), background empirical and theoretical knowledge, and which simplifications, and for which epistemic purpose. All these elements are actually written down in a scientific article (at least those that concern a model), and ‘re-constructing the model’ means that you have to look for them in order to figure out whether you can use it for your purpose, etc.

7. Re-constructing scientific articles.

1. So, let’s adopt the following slogans:
2. Scientists construct scientific models (rather than discovering the world behind the observable phenomena, e.g., by a blind flash of inspiration).
3. Many (but not all) scientific articles present the construction of a model. Very often, it is not a completely new model, but improving an existing model, or applying an existing model to other systems, or experimentally testing whether this can be done, or ‘fitting out’ (measuring) the parameters of a model for a specific system, etc.
4. Models are about a (often very specific) *phenomenon*. For instance, a property or a process or a system. This property or process or system may be physical, but in electrical engineering, it also is, e.g., mathematical or logical. Electrical engineering, as far as I understand it, often concerns processing analogue signals or digital information, such as ‘smoothing’, ‘reducing noise’, filtering, splitting, deciphering, efficiently storing, reliably transferring, transforming, translating between heterogeneous systems, etc. Scientific research in this field also works with phenomena, which are about the behaviour (‘properties’ and ‘processes’ of these signals). Next, the task a researcher takes on is to scientifically model these kinds of phenomena.
5. Models of phenomena are built/constructed for specific epistemic functions. For instance, the epistemic function of the scientific model is to reliably transform a signal with such and such qualities to something else.

6. This former point involves that the way in which researchers <u>construct a scientific model already (to some extent) involves the epistemic purpose</u>. The model must not be true about some independent world, but adequate for its use in predicting or explaining e.g., the behaviour of the systems we are interested in. This in part justifies the acceptance of it. The researchers claim that this model is appropriate for such and such epistemic purposes.
7. Note that this is where scientific research and technological design meet! Scientific models are constructed for specific epistemic purposes. The resulting epistemic tool (i.e., the scientific model) enables scientists and engineers to thinking about, for instance, the design or optimization of a system, the production of a material property, etc.
8. Related to the epistemic purpose, <u>different kinds of models</u> can be constructed for the same system.
    a) A model may be explanatory (that is *causal-mechanistic models*). It explains the causes and mechanisms 'behind' a phenomenon. These kinds of models help in thinking about how to technologically intervene with the system: how can we change or improve or even, create it (such as the ideal heat-engine).
    b) Another type is *mathematical models*. By means of fundamental or axiomatic theories such as Newtonian mechanics or Maxwell's (EM), or thermodynamics , we construct mathematical models. Conversely, we may also do this by finding mathematical formulae that fit the data (as Newton and Maxwell did, but also, as we do in many cases that are much simpler, such as Hooke and Boyle). The epistemic purpose of mathematical models is, for instance, quantitative predictions, or building computer simulations of a system, or designing a control-system, etc.
    c) In electrical engineering (and informatics) a model may be *logical or formal*. In this case, the model aims to represent <u>specific kinds of relations</u> between components of a system (e.g., relations between signals, and how these are transformed by specific types of components) – these are often presented as *diagrams* (or *circuits*). The epistemic purpose of this type of model (the diagram), is, for instance, designing hard-ware or computer simulations, or as a tool for thinking about a system (e.g., how to make it simpler, more efficient, or more robust).
    d) Fundamental work is often done when a *conceptual model* is proposed. [An example is how Edsger Wybe Dijkstra in his *Notes on Structured* Programming (1972) argued the need for techniques to reason about the correctness of programs and what kind of techniques can be used to be confident about the correctness of large programs. The book reflects on the way we (humans) understand the behaviour of computer programs. This includes his emphasis that programs and proofs of correctness should be short and comprehensible. A mathematical foundation of programs is not enough for creating correct programs. The art of programming should also include a sound and understandable way of reasoning about programs and algorithms and a clear decomposition of programs into subprograms. Dijkstra's book is interesting because it explains *why* -- also in 'signals' and computer programs -- we search for simplifications and systematization by searching for specific 'properties' of these kinds of systems. In brief, proposing a new *property* of a system is conceptual work (or a conceptual model).]

   e) From the above, you can also see that more than one model-type may be constructed for a specific system, depending on the epistemic purpose.
9. Finally, models are not built from scratch. Researchers use theoretical principles, fundamental theories, existing models of a phenomenon, empirical knowledge, specific concepts, etc. in the construction of a model.

As has been said, many (but not all) articles published in scientific literature can be understood as presenting a scientific model. My advice is that you are better equiped to understand them if you have in mind that these kinds of aspects play a role in how the model is constructed, and subsequently, in what you have to look for if you want to understand it; or to see what is new about it; or to know whether you can use it yourself; or whether you need to improve/change it, etc. Additionally, understanding the character of scientific models will help you in more easily understanding other scientific fields. You know what to look for, and you know what to ask.

The list below summarizes those questions, which tell what to look for in reading a scientific article. And also, how to be clear and explicit about important aspects in the set-up of your own research.

Note for the assignment: Not every article is about scientific models. On the other hand, scientists who construct a model will not always call it a model; neither will they speak about a phenomenon (but often, about a problem or property or process, etc). This is an exercise, therefore, aim to choose an article that allows you to do this exercise well. Below is a list of the questions for analysing an article. It is important to see that these questions are mutually related. You must work through them keeping in mind their mutual relationship (e.g., if you describe the phenomena, you must make sure that the model is indeed about this phenomenon).

B&K theory: Scientific models 'comprise' several aspects; these aspects are 'build-in' the model. (Re-)construction of a scientific model as presented in scientific literature involves questions as "What is ..":

0 The technological problem context. This question is specific for the engineering sciences and other applied sciences. The way in which such a problem is translated into a scientific research project is to pick-out one of the phenomena held responsible for part of the problem. [An example is problems such 'precipitate formation', or fouling etc of surfaces in catalytic processes, or in the use of membranes etc.; other examples are problems concerning 'efficiency', 'selectiveness,' specificity, etc.] Subsequently, the approach of the research is very similar to every other scientific research, covered by the points below.

i. The object or phenomenon (X) for which the 'model for X' is produced. [X is a phenomenon or process or system that must be described or explained]. This probably is the most difficult part of the re-construction. The phenomenon is not the problem-context within which the research is done (e.g., more efficient such and such). Usually it is much more 'tiny' and modest than doing the big things promised in the introduction of an article! Be very precise about which phenomenon exactly is modelled. In some cases it is helpful to also describe the system or technological instrument that produces the phenomenon under study.

ii. Model type (e.g. morphological, logical, functional, mathematical, causal-mechanistic). [See notes above]

iii. Function or intended 'epistemic purpose' of the model. [A model is constructed for producing specific knowledge about X, e.g., in order to control or produce or intervene with X]
iv. Relevant (physical) circumstances and properties. [Which are the physical conditions that affect X – these are incorporated in the model.]
v. Measurable (physical) variables. [The model must be related to the by indicating which data are measurable or observable.] . In some cases it is helpful to also describe the system or technological instrument by means of which these variables are measured.
vi. Idealizations, simplifications, and abstractions. [Which factors relevant to X are neglected or simplified. This question is related to iv. In order to know for which epistemic purposes the model can be used, and how it could be improved, it is important to specify this.]
vii. Knowledge and principles used in the construction [In constructing a model scientists make use of empirical and theoretical knowledge – **this is part of the justification of the model**!]
viii. Justification or testing of the model [How do scientists justify or test the model? Testing whether a model is fitting (or empirically adequate) can be done by predicting measurable or observable consequences. . In some cases it is helpful to also describe the system or technological instrument used for testing the model.

---

[i] Original articles:

- Boon, Mieke and Knuuttila, Tarja (2009) *Models as epistemic tools in engineering sciences: a pragmatic approach.* In: Philosophy of technology and engineering sciences. Handbook of the philosophy of science, 9 . Elsevier/North-Holland, pp. 687-720. ISBN 9780444516671.
- Knuuttila, Tarja and Boon, Mieke (2011) *How do models give us knowledge? The case of Carnot's ideal heat engine.* European journal for philosophy of science, 1 (3). pp. 309-334. ISSN 1879-4912.
- Link to UT Repository http://doc.utwente.nl/view/author/151893977.html