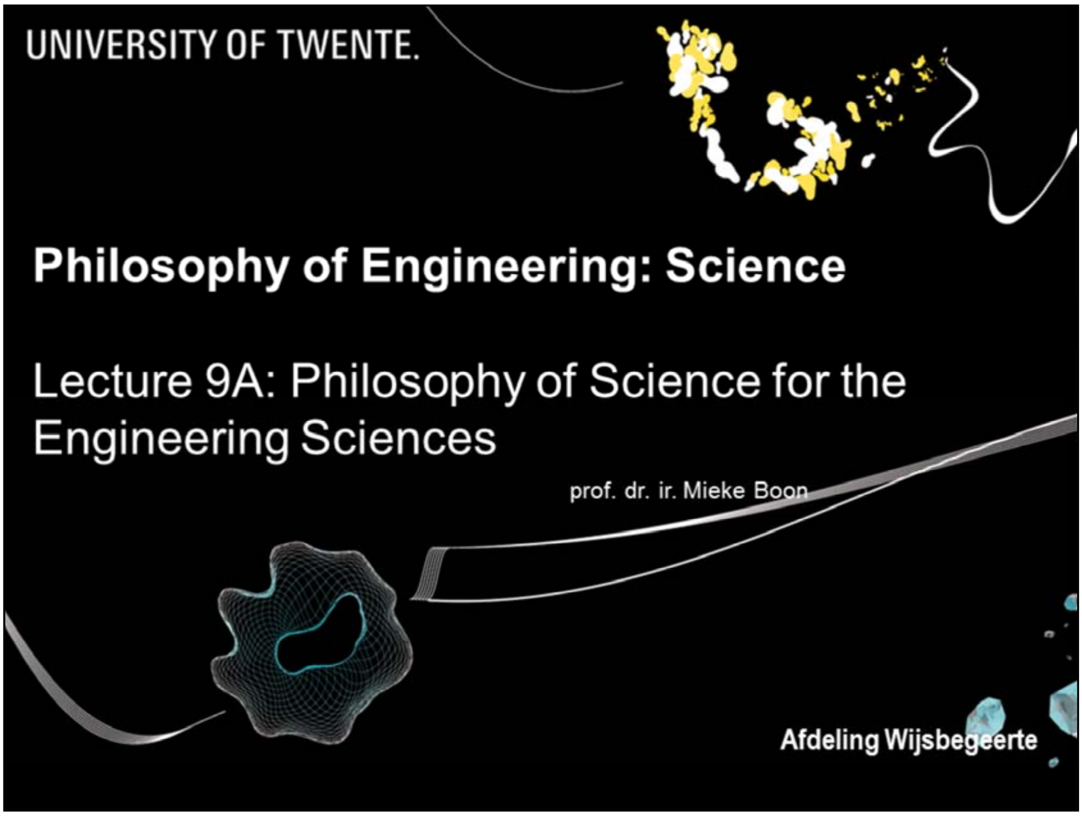



**General philosophy of science versus a philosophy of science for the engineering sciences**

Why would a *philosophy for the engineering sciences* be different from 'general' *philosophy of science*? In the first four lectures of this course, we have mainly addressed issues of the latter. However, general philosophy of science may not address issues that are of particular importance to understanding the specific character of the engineering sciences. Important differences between general philosophy of science and a philosophy of science for the engineering sciences are:

I. <u>What is science?</u> They have different ideas on what science 'really' is: the paradigm example of the former is theoretical and experimental (fundamental) physics, whereas the second focuses on examples in the engineering sciences.

II. <u>What is the aim of science?</u> They have distinct ideas on what is the aim of science. General philosophy of science assumes that science aims at *true* theories (they are very much theory focused), whereas a philosophy of science for the engineering sciences assumes that scientific research aims at knowledge that can be applied in the design and development of technology. Phenomenological laws and scientific models are important aims of science. The important criterion is not their truth, but their epistemic usefulness.

III. Therefore, PhoSc versus PhoEngSc are concerned with different kinds of problems.

Truth, objectivity and rationality are very important issues in the PhoSc. One way of achieving truth and objectivity is by excluding the role of the knower (the scientist, the so-called 'epistemic agent'). Accordingly, in explaining science, PhoSc has focused on the relationship between knowledge and world, since including the role of the scientist would make it subjective. PhoEngSc, on the other hand, is firstly interested in the epistemic usefulness of scientific knowledge, which implies that a PhoEngSc must include the role of the scientific researcher as an 'epistemic agent' (as a cognitive and intellectual being). In PhoEngSc, therefore, focusses on empirical adequacy and epistemic usefulness of scientific knowledge.

IV. The PhoSc, in an attempt to secure truth and objectivity of scientific knowledge, has made a distinction between the so-called *context of discovery* and the *context of justification*. PhoSc assumed that 'in the end' the way in which discoveries are made, the way in which scientists produce hypotheses is irrelevant to the truth of scientific knowledge. The way in which theories are constructed is irrelevant to their justification, according to PhoSc, and therefore not a subject worth philosophical attention. Investigating how discoveries are made, or how scientific knowledge is constructed, according to PhoSc, is the domain of psychology, not of philosophy. PhoSc should focus on the *context of justification*. The topics of PhoSc has been the subject of the first half of this course (with focus on questions such as: how can theories be proven, and what does it mean that theories are true). PhoEngSc, on the other hand, argues that the way in which scientific knowledge is constructed must be taken into account in appropriate philosophical understanding of science. This is why in the last few classes, we have focused on the question of how scientific knowledge is constructed. PhoEngSc argues against PhoSc that part of the justification of knowledge is already in the construction of knowledge.

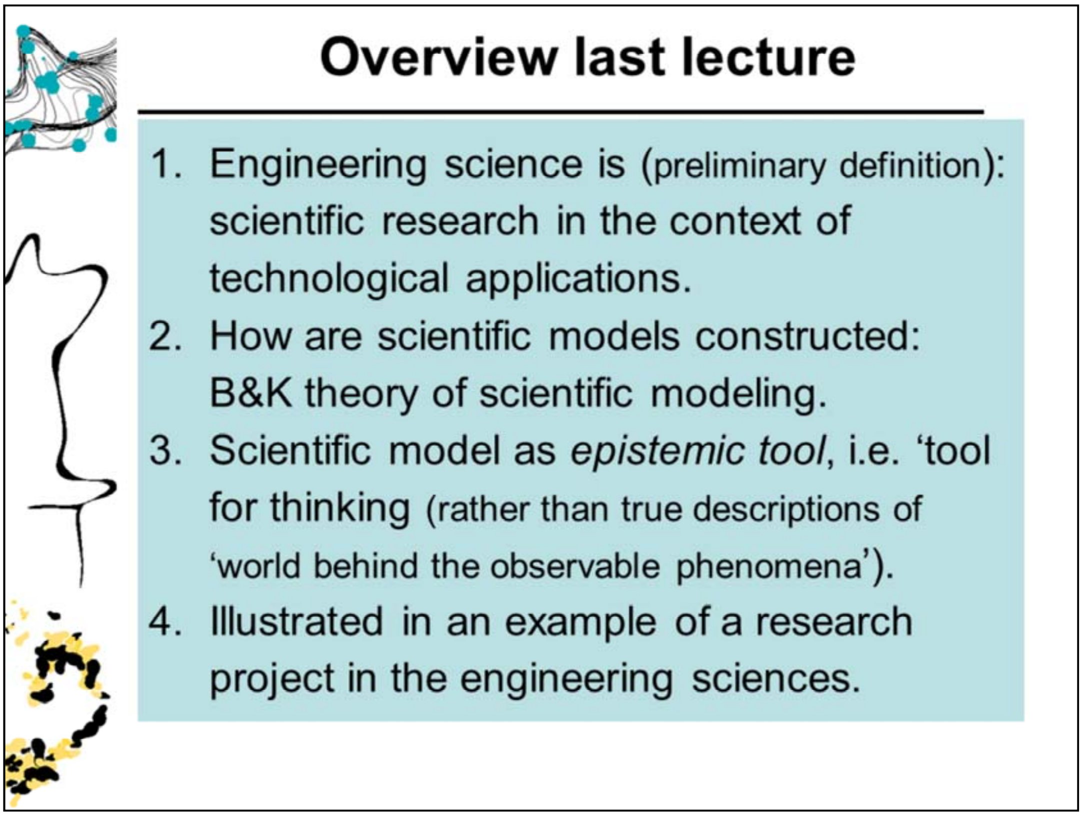
V. As a consequence of the former, the role of measurement instruments, experimental set-ups, and technology in general is mostly neglected in PhoSc, whereas in a PhoEngSc, including 'technology' will appear crucial to a proper understanding of the engineering sciences. See for instance the section on 'what are phenomenological laws.'

VI. It may be defended that the proposed PhoEngSc is appropriate to all of science (in particular the natural sciences), but this is beyond the scope of the course.

In sum, whereas in this schema, PhoSc has put emphasis on the bottom part of the HD-model (the <u>justification</u> of knowledge), PhoEngSc adds in putting emphasis on the <u>construction</u> of knowledge, which is expressed in these schema's.

# Overview: Metaphysical ideas

1. *Scientific realism*: Scientific knowledge is an (approximately) literally true description of 'world behind phenomena' or 'unobservable phenomena,' *explaining* observable phenomena.
2. *No-miracle argument* supports scientific realism: assuming the (approximate) truth of scientific knowledge is the best explanation for the successes of science (e.g., for its explanatory and predictive power).
3. Anti-realism argues that we cannot make sense of *true* knowledge of unobservable phenomena.
4. Can an *anti-realist* explanation of the successes of science be given?




REPETITION CLASS 6

Examples of Engineering Sciences:

***Electrical Engineering* (e.g.)**

Electrical engineering is concerned with designing devices that convert or transform electrical, electro-magnetic or mechanical input into electrical, electro-magnetic or mechanical output, thereby meeting certain technological functions. Scientific research in the field of electrical engineering proposes models of the *behaviour* of electrical devices. This task differs from the *design* (e.g. of electrical circuits) of such devices.
Scientific articles aim to contribute to optimizing the devices with regard to their functioning.

***Materials Science* (e.g.)**

Materials engineering: 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

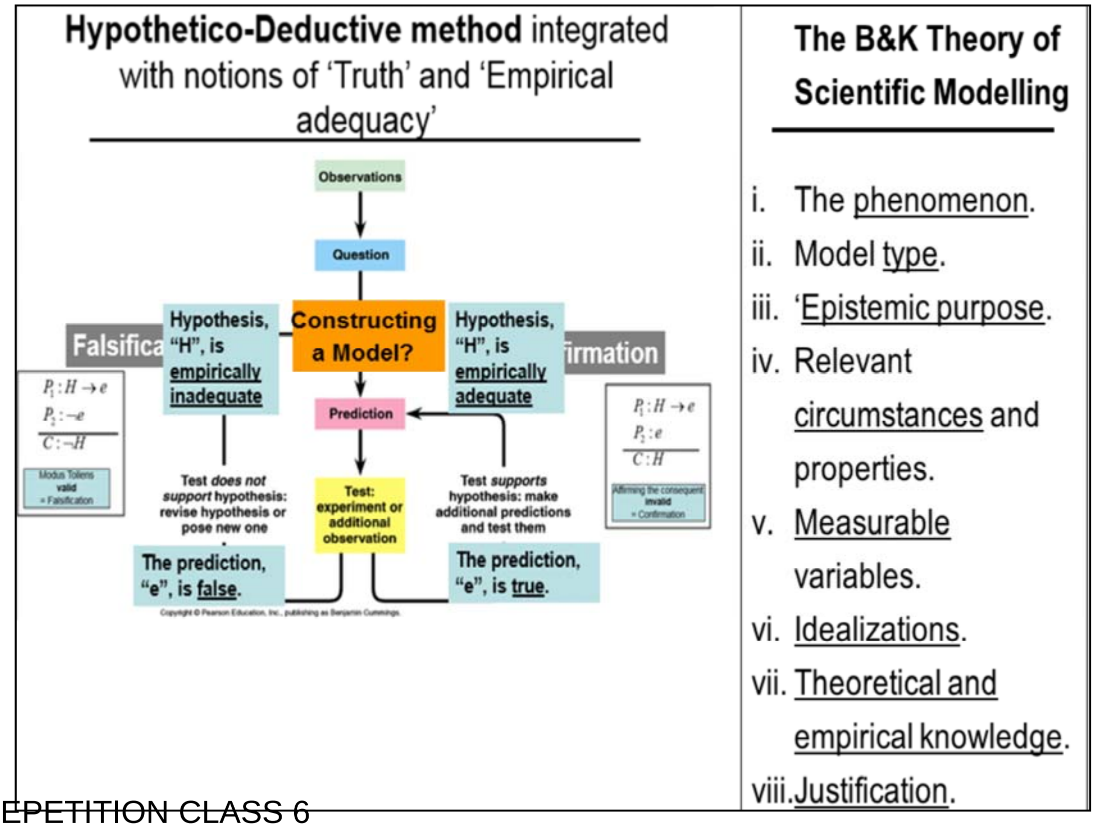
higher temperatures, and polymers of a particular strength.
Materials science: scientific understanding of materials – either of materials that already exist or of materials that scientists aim to create artificially – which may then indicate ways in how to create or intervene with specific material properties.
Scientific articles aim to contribute to optimizing or creating material properties with regard to their functioning.

**Chemical Engineering** (e.g.):

•Chemical engineering: 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.

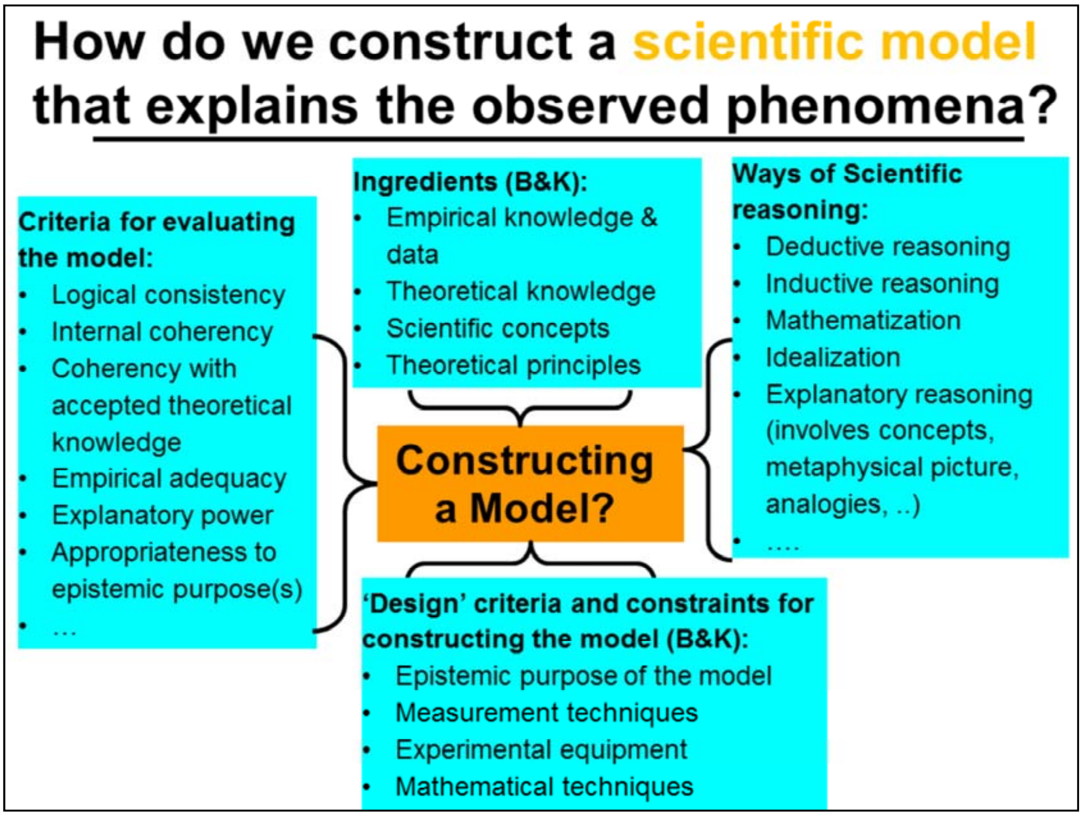
•Scientific research in the field of chemical engineering proposes models of the behaviour of chemical devices. It typically proceeds through studying the behaviour of devices by interpreting them in terms of physical phenomena considered to be relevant to their proper or improper functioning, and then 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.

•Scientific articles 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.




REPETITION CLASS 6

The hypotherico-deductive method illustrates important aspects of research, and their connections. It focuses on how to test the hypothesis, but does not explain how a hypothesis (a phenomenological law, a scientific model, etc.) comes about. Therefore, the general hypothetical-deductive model of aspects and dynamics in scientific methodology applies to scientific research in the engineering sciences as well. The B&K theory of modeling proposes that modeling involves a number of ingredients, which can usually be found in models, helping us in understanding how they are constructed.




REPETITION CLASS 6

We have discussed that constructing a model (1) makes use of empirical and theoretical knowledge; we never start from scratch. (2) We employ different kinds of reasoning such as to construct a model that (3) meets specific criteria, which in turn must be chosen such that (4) several other constraints in the 'design' of the model will be met, namely, the epistemic purpose of the model, but also the mathematical and experimental instruments that we have at our disposal. In the past when computers were less powerful, for instance, the mathematical structure of the model was made such that analytical solutions were possible, or just simple computer simulations. Similarly, available measurement-techniques and experimental equipment put constraints on how the model is constructed. In modelling, we aim to avoid variables that are not measurable, since measurements are the link between the scientific model and real-world target-system.

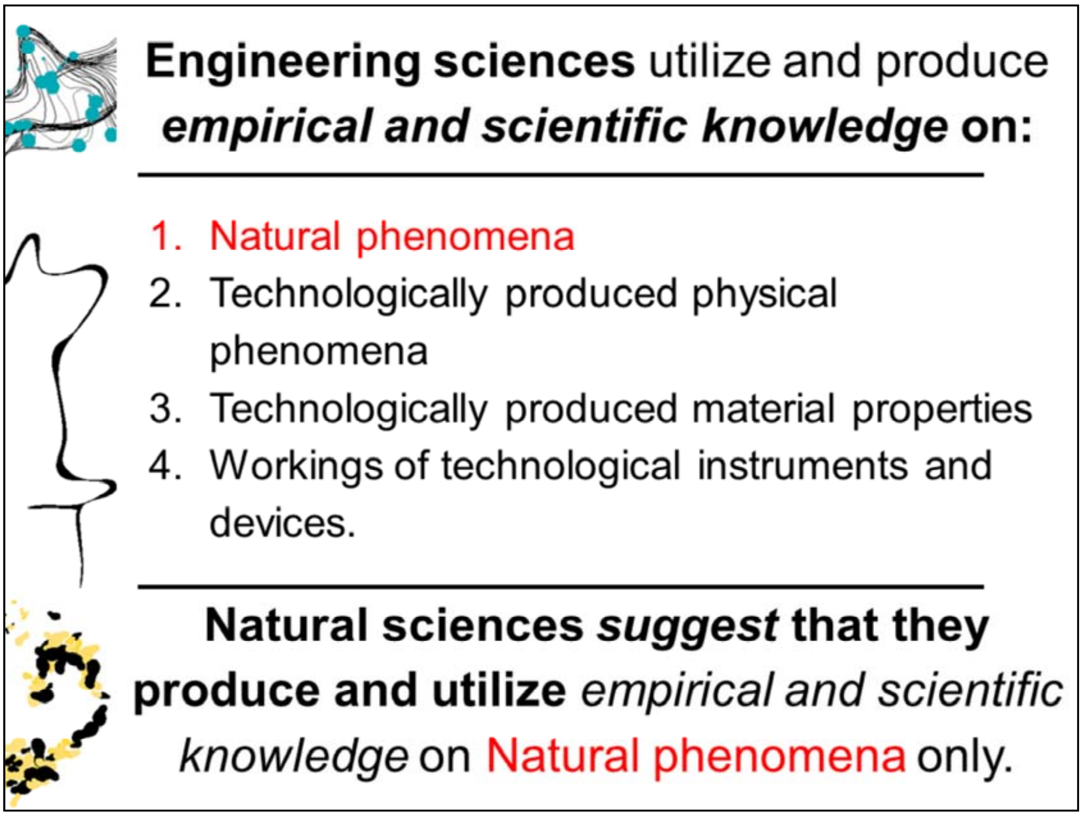
How is this schema related to the ingredients in the B&K theory? The B&K theory points out which ingredients are part of the model, but does not explain how the model is constructed. In this schema several aspects are added to account for the actual construction of the scientific model. Beside making use of the ingredients, the construction of the model involves:

(1) Different types of reasoning: not only logical ways of reasoning, but also mathematical reasoning, idealization, and explanatory reasoning, and,

(2) Criteria for evaluating the model: the model must be constructed such that it is internally consistent and coherent (parts of the model must hang together); the model must also be coherent with (i.e. not contradicting) accepted theoretical knowledge; and it must be empirically adequate (that is, its predictions must agree to relevant empirical knowledge and relevant measurements in testing the model); and also, related to the *epistemic purpose* of the model, a pragmatic criterion is involved, which says that the model must be appropriate for the epistemic purpose.

# Topics of lecture 9

1. What is knowledge in the engineering sciences typically about – How is this different from the natural sciences (physics, chemistry, ..)? ..
2. ..




REPETITION CLASS 6

**Empirical and scientific knowledge about what?**

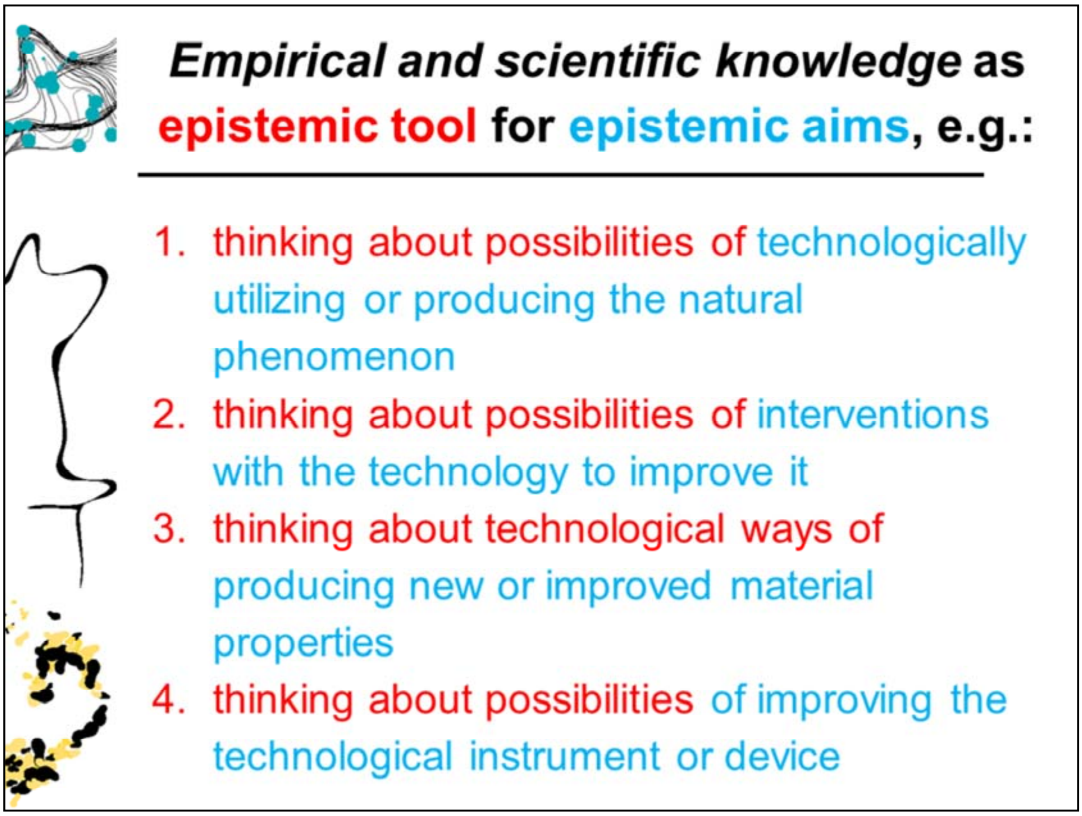
The idea of scientific knowledge (phenomenological laws, laws of nature, scientific models, scientific concepts, axiomatic theories) as *epistemic tool* (rather than a literal description or picture of 'the world *behind* the observable phenomena') is an important idea of *a philosophy of science for the engineering sciences*. When considering the natural sciences (e.g., fundamental topics in physics and chemistry) the generally accepted idea is that scientific knowledge is generated for its own sake: we just want to know; we just want to know what the world 'really', or 'fundamentally' is like. But in the engineering sciences, we usually produce empirical and scientific knowledge in view of specific (technological) applications. We may distinguish between different types of subjects of empirical and scientific knowledge produced in scientific research:

*a.* *empirical and scientific knowledge* of natural phenomena. For instance, the natural phenomenon of bacteria in nature that oxidize mineral sulfides. Empirical knowledge consists of knowledge about the physical and/or technological circumstances at which this phenomenon manifests. Scientific knowledge consist of phenomenological laws that mathematically 'describe' the observed phenomena, and secondly, of scientific models that 'explain' the observed phenomena.

*b.* *empirical and scientific knowledge* of technologically produced physical phenomena (e.g., the phenomenon of expanding and contracting steam in a heat engine; the phenomenon of super-conductivity),

*c.* *empirical and scientific knowledge* of all kinds of technologically produced material properties (e.g., chemical composition, chemical structure, crystal structure, material density, melting temperature, and the conductivity and electrical resistance of materials),

d. and we also produce *empirical and scientific knowledge* of the workings of technological instruments and devices (think of microscopes, thermometers, atomic force microscopes, chemical processes, electrical devices, etc.).




REPETITION CLASS 6

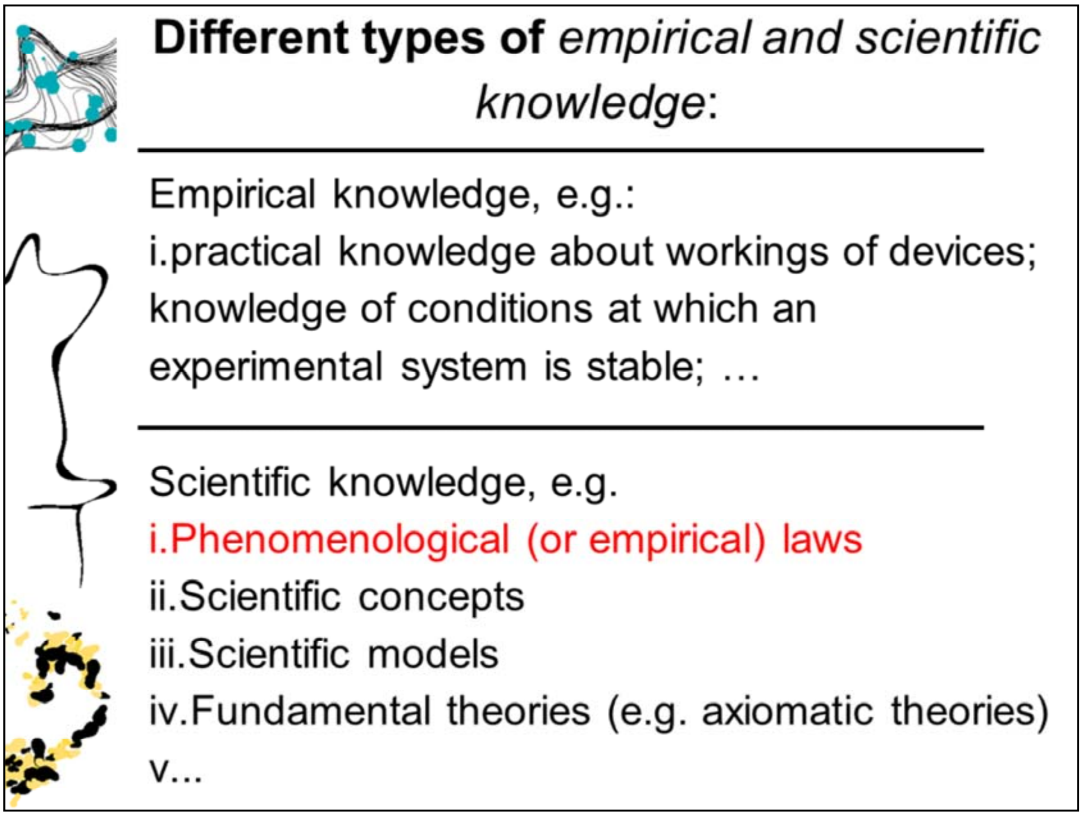
**Different types of empirical and scientific knowledge**

In all these cases, we construct ('build') knowledge, such as a phenomenological law 'describing' a phenomenon (see explanation in next section) and/or a scientific model of it, for specific 'epistemic aims.' In the engineering sciences we aim, for instance, at scientific models that can be used as epistemic tools in technological design, development and innovation. For instance, scientific models are used for different kinds of epistemic aims:

- (ad a) thinking about possibilities of technologically utilizing or producing the natural phenomenon for performing technological functions (e.g., a technology that is based on the design-concept of the phenomenon 'artificial photosynthesis for converting sunlight in electricity'),
- (ad b) thinking about possibilities of interventions with the technology to improve or optimize it, or, making computer-models for computer-simulations in which all kinds of technological interventions can be tried (e.g., once they have a rudimentary technology for artificially producing electricity from sunlight,

researchers will aim to make it more efficient, more technologically robust, etc.)

- (ad c) thinking about technological ways of producing new or improved material properties for performing (improved) technological functions (e.g., materials used in chips, in solar-panels or in batteries).
- (ad d) thinking about possibilities of improving the technological instrument or device (e.g., this may involve new design-concepts for producing the same technological function – in the example above, artificial photosynthesis is a new design-concept that may solve the problem of low efficiency in traditional solar-panels).




REPETITION CLASS 6

**Different types of empirical and scientific knowledge**:

Empirical knowledge, e.g.:

i. practical knowledge about workings of devices; knowledge of conditions at which an experimental system is stable; …

Scientific knowledge, e.g.

i. Phenomenological (or empirical) laws

ii. Scientific concepts

iii. Scientific models

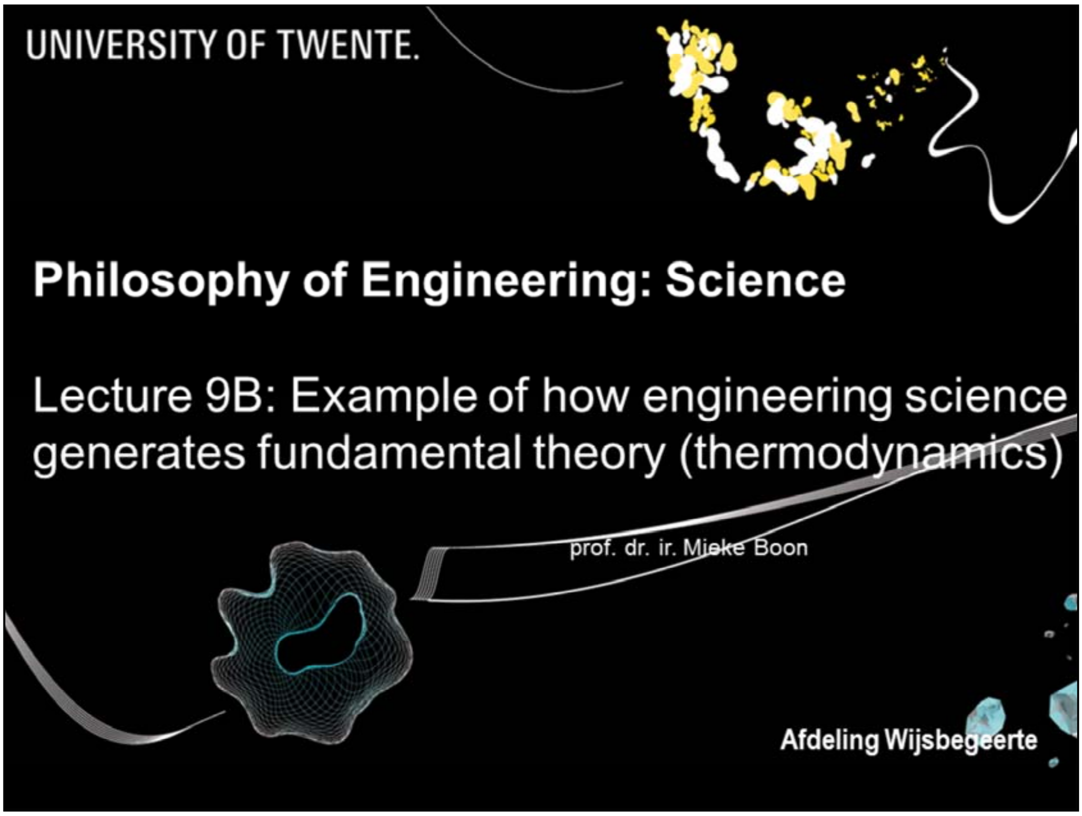
iv. Scientific theories (e.g. axiomatic theories)

v. ..

## Take home - Overview

- In the engineering sciences, empirical and scientific knowledge is about naturally and technologically produced phenomena, and technological devices.
- Different types of empirical and scientific knowledge: phenomenological laws, parameters, scientific concepts, scientific models, fundamental theories.
- How is this knowledge constructed?
    - Bricolage: we use empirical and scientific knowledge – similar to design.
    - Constrained by our cognitive capacities and available mathematics and technologies.
    - Crucial role of measurements in constructing scientific knowledge.

REPETITION CLASS 6


UNIVERSITY OF TWENTE.
Philosophy of Engineering: Science
Lecture 9B: Example of how engineering science generates fundamental theory (thermodynamics)
prof. dr. ir. Mieke Boon
Afdeling Wijsbegeerte

## What is engineering science?

1. **Engineering science is scientific research in context of technological applications.**
2. Engineering sciences strive to understand, predict or optimize the behavior of devices, and/or the properties of diverse materials, whether actual or possible.
3. The behavior or property is the phenomenon studied.
4. Engineering sciences aim at models for these phenomena (rather than at universal theories) – these models are presented in scientific literature.
5. 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 behavior of different devices or the properties of diverse materials.
6. Engineering sciences aim at creating, controlling and improving **technical functions**.

***Example of how a technological idea or problem is translated to a research question***

What is technological function of paint?
1.Technological function includes qualities such as protecting a surface, workability in its application, durability and aesthetic qualities.
2.Dysfunctions of paint are properties such as, the tendency to maintain ripples; the increase of its viscosity when applied at higher temperatures; the tendency to capture air-bubbles; the toxicity of the solvent; its poor scratch-resistance; formation of cracks in hardened paint; loss of color; and, the tendency to turn yellowish under the influence of sun-light.

Above, it was claimed that ‘scientific research in a technological application contexts’ is characteristic for the engineering sciences. The question is then, how a technological application or a technological problem is ‘translated’ into a scientific research question?

In light of this question, very generally put, **technology can be characterized as ‘the performance of a technological functions’**. This implies that scientific research in the engineering sciences aims at creating or improving a technological function. Examples that can be given of technological functions are endless. You can think of technological functions performed by material properties such as electrical resistance, electrical conductivity, conductivity of heat, material elasticity, and other physical and (bio)chemical workings of materials. Additionally, technological functions are performed or achieved by (physical) processes, such as the production of electricity, the transfer of a signal from location A to B, the transformation of a physical process such as sound into an electrical signal, the production and control of an electro-magnetic field (such as in MRI), the production of a chemical compound, etc.

In high level engineering sciences, technological functions sometimes are conceptualized at a more abstract level, sometimes referred to as 'design concepts'. Researchers conceptualize the technological function without exactly knowing as yet how to produce it. The idea of a technological function is than abstracted from the way it is 'normally' produced, or, even more innovative, the technological function is newly thought up by means of analogies. Examples of the latter can be found in so-called 'biomimicking' approaches (e.g., http://www.youtube.com/watch?v=nVOzkO-ccuc): Researchers discover certain valuable properties or processes in nature, and aim to mimick it by technological means. Sometimes this involves aiming at technologically producing an exact copy (such as the 'artificial', chemical production of medicinal compounds discovered in nature), but often it does not involve to make an exact material copy, but instead, to aim at performing the same function with some other technological means, that is, 'to steal the ideas from nature' as Joanna Aizenberg from Stanford University puts it in this TEDX. Another example is 'artificial photosynthesis': leafs are able to transform the energy from sunlight to energy and chemical compounds in a rather efficient manner [e.g., Pandit A., H. de Groot, and A. Holzwarth, eds. (2006) "Harnessing Solar Energy for the Production of Clean Fuel." White Paper by an international task force under the auspices of the European Science Foundation. ISBN 978-90-9023907-1 ]. These biochemical processes involve the electrochemical transfer of electrons to a higher energy-level. The challenge for researcher is to find other molecules (which should be chemically stable and can be produced in large quantities) that can be used for the 'artificial' conversion of sunlight to electricity or electrical energy containing molecules.

Very often, scientific research in the engineering sciences aims at improving existing technologies. In that case, the malfunctioning is addressed. See the examples on this slide: it lists examples of how the technological function of paint could be, or has been improved. The (mal)functioning is described in terms of material properties that should be achieved or improved or prevented, etc.

Note that the physical phenomenon (property or process) that is considered to be responsible for the (mal)functioning of a technological device (in this example, paint) becomes the research topic. In this course it has been proposed that scientific research, besides other things, aims at **scientific modeling of a phenomenon**. You can now easily understand why and how the **B&K approach for (re-)constructing scientific models applies**. That is, you may now see that this idea on scientific methodology (of how to construct a scientific model for a phenomenon) also applies for the engineering sciences. In brief, in scientific research technological (dys)functions are understood in terms of physical phenomena held responsible for the (dys)functioning of the technological device. This application context is guiding in scientific research of the engineering sciences. Researchers aim to produce a scientific model such that it meets the epistemic purpose of the model: that is, they aim at a scientific model that enables them to think about solutions or improvements of the technological function. Hence, besides other things (such as getting the technological instruments and procedures working) they aim at **constructing an epistemic tool** (the scientific model). These models are published in scientific articles.

**The B&K Theory of Scientific Modelling:**
(Re-)construction of a model (e.g., as presented in scientific articles) involves asking: “What is ..”:

0. What is the technological problem to be solved?
i. Specific phenomenon (X) for which the ‘model of/for X’ is produced (**+ instruments producing it**).
ii. Model type (e.g. morphological, logical, functional, mathematical, causal-mechanistic, statistical, ..).
iii. ‘Epistemic purpose’ of the model.
iv. Relevant (physical) circumstances and properties.
v. Measurable variables (**+ instruments measuring it**).
vi. Idealizations, simplifications, and abstractions.
vii. Theoretical and empirical knowledge, and principles, used in the construction of the model.
viii. Justification of the model (**+ instruments in testing**).

In the engineering sciences, we usually start from a ‘problem-context’: a technological problem we wish to solve, or a technological function that we want to generate. Therefore, the very first question should be: *What is the technological problem to be solved*?

Often, a technological problem or a technological (dis)function is understood in terms of a (physical) phenomenon held responsible for the problem of (dis)function.

## Scientific research in the engineering sciences: A historical example

Research project in Engineering Sciences:

**Optimization of steam engines**

Newcomen engine (1712)

So far, concerning the **specific character of the engineering sciences**, the following idea has been introduced:

(1) The application context within which the engineering sciences perform scientific research is technological functions 'brought about' by technological instruments and procedures.

(2) Technological functions are understood in terms of (physical) phenomena held responsible for the (dys)function.

(3) Scientific research (besides other things) aims at constructing scientific models of these phenomena – often related to relevant aspects of technological devices or procedures.

(4) These scientific models should be constructed such that they enable researchers to think about improvements etc. of the technological function. Hence, the scientific model that researchers construct for the phenomenon under study must be apt as an epistemic tool.

(5) The B&K theory of (re)constructing scientific models is applicable for understanding (this part of) the methodology of the engineering sciences.

**Applying the B&K approach (= analysis).**

In the next part of this class, this general idea about the engineering sciences, and the B&K theory for reconstructing scientific models will be applied to an example from the engineering sciences, namely, the model of the ideal heat-engine as it was constructed by Sadi Carnot (in 1824).

The relevance of learning to apply the B&K theory for reconstructing scientific models is that it, once you have become used to it, helps in understanding more easily scientific work, especially in fields you are less familiar with. It invites you to study scientific knowledge presented in textbooks, the internet, or scientific articles. Most of us take scientific knowledge firstly as representations of what the world is like. This is also how we are often educated. Textbooks in physics, for instance, often present theories without any reference to the technological devices that enabled the construction of that theory. A striking example is thermodynamics [Wikipedia presents an overview of thermodynamics that is much richer than many textbooks http://en.wikipedia.org/wiki/Thermodynamics], but also E&M.

Usually, (fundamental) theories such as E&M and thermodynamics are easier to understand – and become less abstract, but instead, connected with technological applications – if you understand how these theories where constructed. The point is to see that such theories often were constructed in the context of specific technological devices and experimental procedures. In the case of E&M, Maxwell's construction of his theory was 'enabled and guided' by previous EM experiments, involving instruments, observations, measurements by Faraday, Ampère, Orsted and others. Maxwell's EM theory is firstly 'about' these technologically produced physical phenomena (see slide 37 of lecture 5).

**Example of Engineering Science: The emergence of thermodynamics (scientific research) in the context of the development of steam engines (technological application).**

Sadi Carnot is 'the father of thermodynamics'. His scientific model of the ideal heat-engine (also called 'the Carnot engine') is regarded as the starting-point of thermodynamics. He presents this model in "*Reflexions on the Motive Power of Fire and on Engines fitted to develop that Power*" (1824), which develops the first law of thermodynamics:

1. "The increase in internal energy of a closed system is equal to the difference of the heat supplied to the system and the work done by it."

and articulates the second law of thermodynamics:

2. "Heat cannot spontaneously flow from a colder location to a hotter location."

This work is a historical example of engineering science: scientific research in the context of a technological application. The technological application in the context of which Carnot did his scientific work is the steam engine.

It is important to notice that Carnot developed this theory more than a century *after* the first steam engines were built. The movie illustrates the physical phenomenon responsible for the technological functioning of this engine:

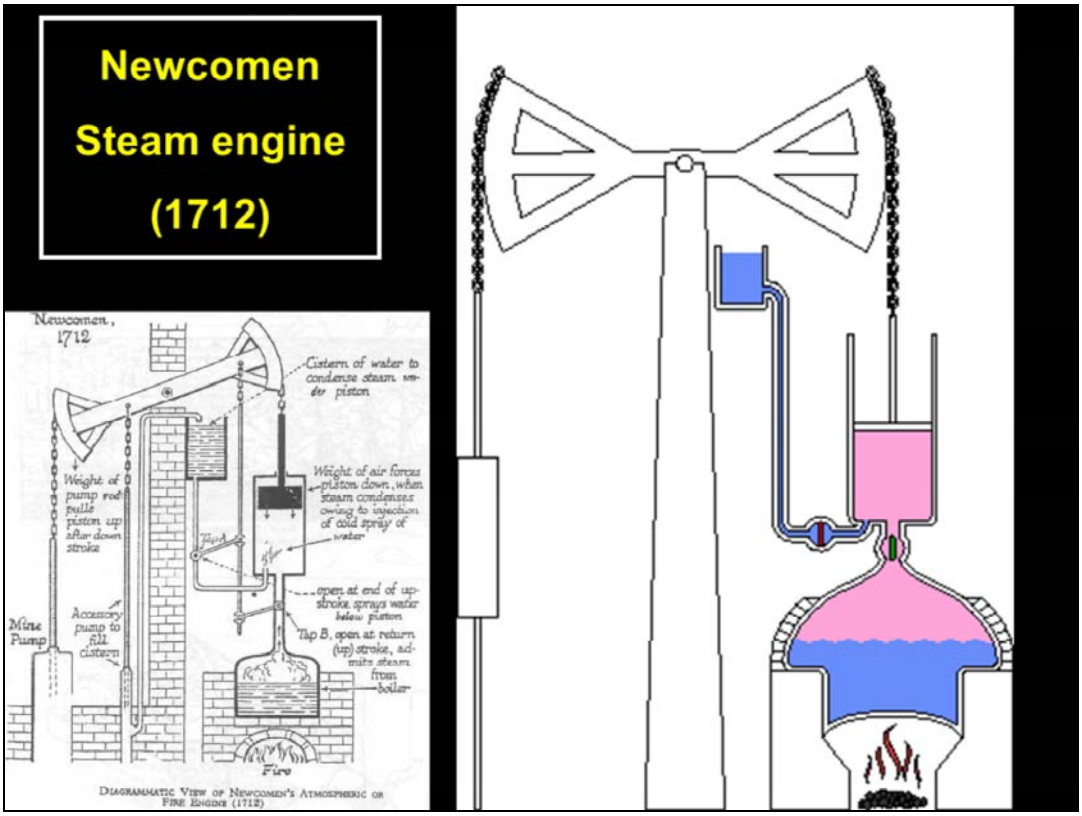
**First step of our analysis (1):**

Technological function of this technological device: producing ‘motive power’ from heat.

Physical phenomenon shown in an experiment: Plastic bottle is filled with hot steam (clearly, this illustration is not historical). Then the plastic bottle is closed. It is crushed if (the steam in) this bottle is cooled down in a bucket of cold water.

**Historical background.**

A black-smith from Davon, Thomas Newcomen, introduced valve timing in 1712 (see next slide for explanation). This steam engine is the first mechanical engine. Better than water-mill or pony power. Starting point of industrial revolution. We now know that less then 1% of the coal was used efficiently. It is called an atmospheric engine (compare with improvement by James Watt below). Cooling the steam in the cylinder creates a vacuum that pulls the piston down (by the atmospheric pressure on the piston). In its early days, steam engines were used to lift water out of the mine. Helped in safety of mine-workers.




**Schematic working of this technological device**, which consists of the following cycle:

(1) The water (blue) in the boiler is heated by the burning of coal by which steam (pink) is formed in the boiler.

(2) When the green valve is opened, steam enters the cylinder that is closed air-tight with a moveable piston. The piston is pushed upwards by the pressure of the hot steam, causing a downward movement of the beam (left side).

(3) If the green valve is closed (when the piston is at its highest position), the red valve is shortly opened and closed again, spraying cold water (blue) in the cylinder, which causes the cooling of the steam in the cylinder.

(4) When the steam cools, the pressure in the cylinder drops, and the piston is sucked downwards, causing an upward movement of the beam (in this movement, water can be pumped away from the mine). [Note that, instead of saying that 'the piston is sucked downwards', you can also say that 'atmospheric pressure pushes the piston downwards'.]

Back to step (2)

**Next step of the analysis (2):**

<u>Technological function</u> of this device: producing 'motive power' from heat.

<u>Physical phenomenon</u> responsible for this function: Atmosphering pressure

pushes a piston downwards if the hot steam in the cylinder is being cooled, which causes motive power of the beam, vice versa.

## Scientific methodology in the engineering sciences?

**Translating a technological problem into a scientific research project:**

- What is technological problem / challenge? and/or What is technological (dis) function of target system?
- Which physical phenomenon is responsible for technological (dis) function(ing)?
- Which knowledge needs to be produced? => What is the epistemic aim of scientific modeling the phenomenon.

**Translating a technological problem into scientific research.**

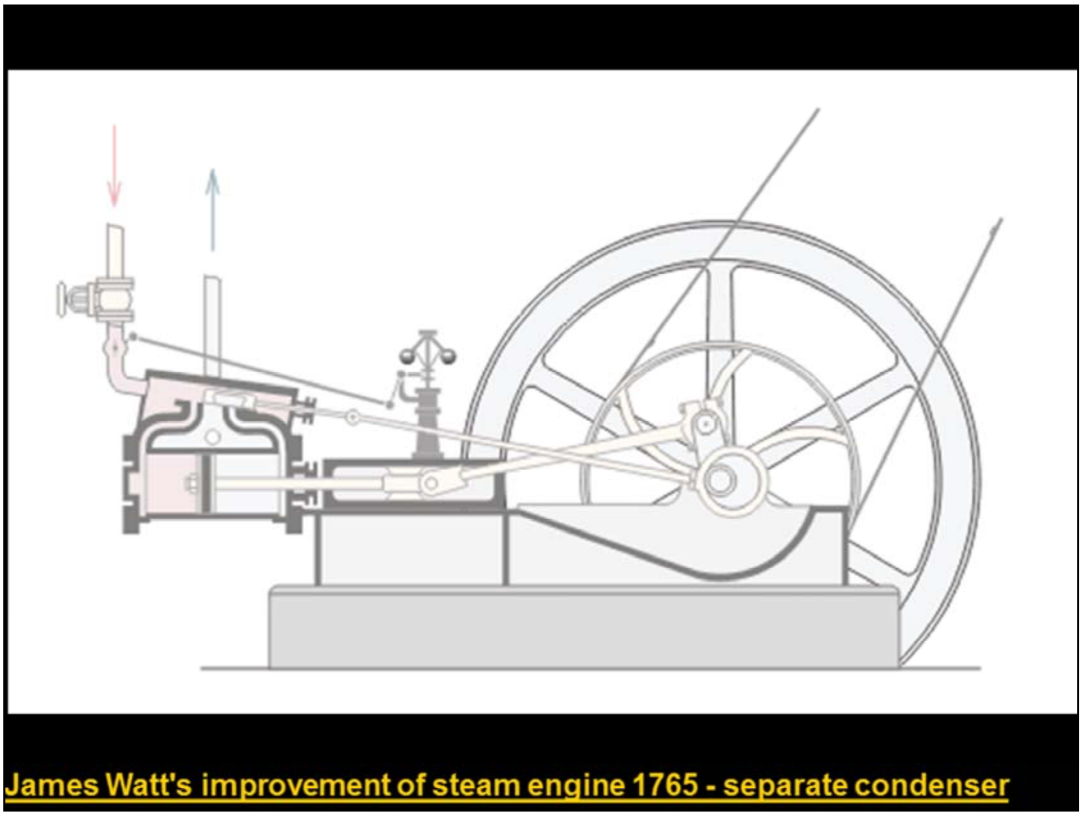
One of the technological problems or challenges for improving steam engines was to reduce the heat-use (i.e., to improve the power to coal ratio – that is, as we call it now: the efficiency).

Recall the general idea: scientific research in the engineering sciences aims at scientific modeling the phenomenon responsible for the technological function. Does the researcher know how to approach the modeling of the phenomenon? Well, he knows the epistemic purpose, namely, to construct a scientific model that enables to researcher (or engineer) to think about improving the efficiency of this device.

**Next step of the analysis (3):**

1. Technological function of this device: producing ‘motive power’ from heat.
2. Physical phenomenon responsible for this function: Atmospheric pressure pushes a piston downwards if the hot steam in the cylinder is being cooled, which causes motive power of the beam, vice versa.
3. Technological problem: Efficiency (ratio between ‘motive power’ and heat or coal use). Hence, the technological challenge is to improve the efficiency.
4. Epistemic aim of the scientific model: Finding ways to improve the efficiency

of this engine.



James Watt's improvement of steam engine 1765 - separate condenser

**Technological improvement of the heat engine by good engineering.**

Improvements of the heat engine were definitely achieved by good engineering work. In other words, technological improvements and solving technological problems <u>often occur without the contribution of scientific research</u>.

This is an example of good engineering work: James Watt, about 50 years later, came with a very innovative design that improved, besides other things, the efficiency of the steam engine (by separating the condenser part).

**Technological improvement of the heat engine by scientific research?**

How, in your view, could <u>scientific research</u> contribute to the improvement of a technology? Try to think of how you would approach the development of a scientific model for the phenomenon in which you take the first part of the analysis into account:

1. <u>Technological function</u> of this device: producing ‘motive power’ from heat.
2. <u>Physical phenomenon</u> responsible for this function: Atmospheric pressure pushes a piston downwards if the hot steam in the cylinder is being cooled, which causes motive power of the beam.

3. Technological problem: Efficiency (ratio between 'motive power' and heat or coal use). Hence, the technological challenge is to improve the efficiency.
4. Epistemic aim of the scientific model: Finding ways to improve the efficiency of this engine.

Students in the engineering sciences often *only* propose engineering solutions, for instance, the common trial-and-error approaches for finding out how changes affect the process. They often have a blind spot for the possible role of scientific research.

So, let us study the scientific approach of Sadi Carnot. It is recommended to try to follow Carnot's way of reasoning in order to recognize the different ways of reasoning. Also, it is important to recognize that Carnot did not use experiments! Nevertheless, he had knowledge of experiments with gasses performed in his time, such as Boyle, Gay Lussac and Mariotte.

Note: The ideal gas law and the Avogadro number was unknown. The measurement of temperature was not fully developed.


**Nicolas Léonard Sadi Carnot** (1 June 1796 – 24 August 1832) was a Frence physicist and military engineer, who, in his 1824 *Reflection*, gave the first successful theoretical account of heat engines, now known as the Carnot cycle, or the ideal heat engine, thereby laying the foundations of the second law of thermodynamics. He is often described as the "Father of thermodynamics", being responsible for such concepts as Carnot efficiency, Carnot theorem, Carnot heat engine, and others (source: Wikipedia).

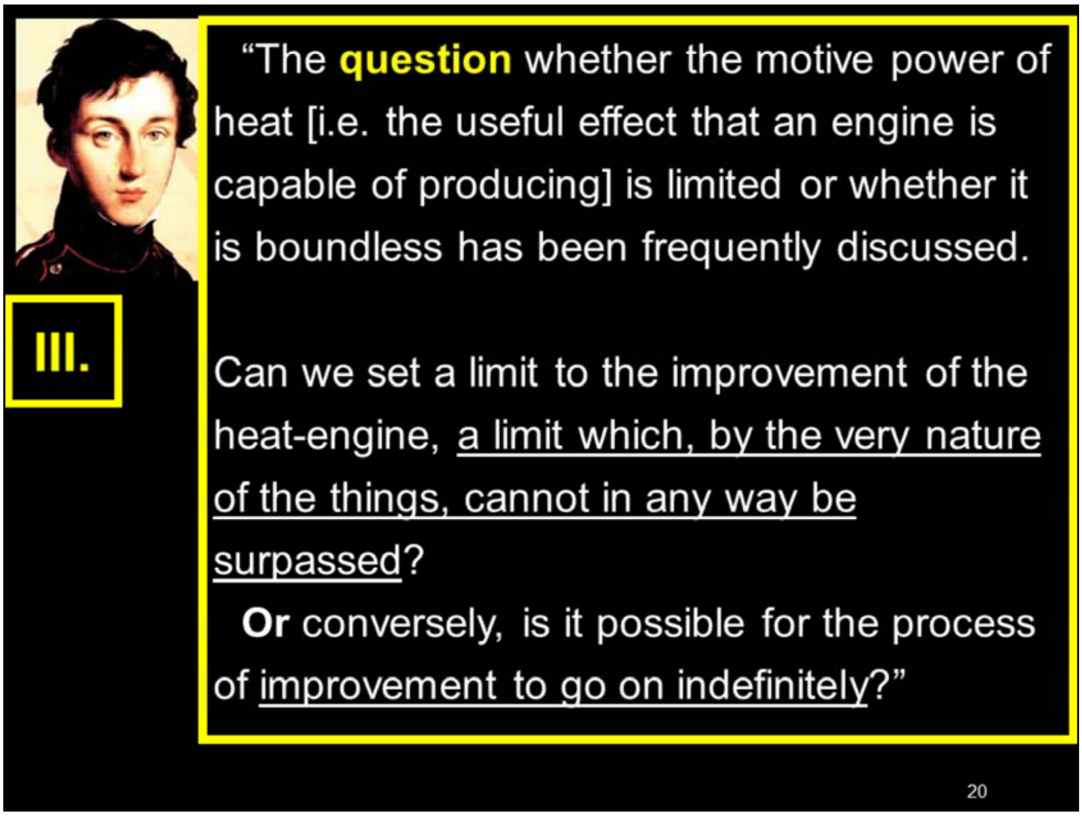
The analysis of Carnot's Reflextions, in the next slides, makes use of: Knuuttila, T. and Boon, M. (2011) *How do models give us knowledge? The case of Carnot's ideal heat engine.* European journal for philosophy of science, 1 (3). pp. 309-334 (see Chapter 4 of this article). As a consequence, several of the comment made above are repeated below in somewhat different wordings.

The reconstruction of how Carnot constructed the model of a heat engine (in our article, Knuuttila and Boon 2012, is primarily based on Carnot's line of argument in *Reflexions on the Motive Power of Fire and on Machines Fitted to Develop that Power* (Carnot 1986, [1824]). Our reconstruction follows the modeling steps of the B&K theory. It should be kept in mind, however, that the modeling steps distinguished in our analysis do not necessarily present the listed sequential order – often these different aspects are modeled in a mutual interaction. Together, they make up a story in the sense that the steps must cohere.

Roman numbers refer to the modeling steps in the B&K theory (see last slides of lecture 4).

Note:

It is worth mentioning that Carnot developed his model by means of formulating assumptions and principles in ordinary language. He did not have at his disposal such representational means as the well-known P-V diagram (see diagram on slide 35) that was invented by Benoît Paul Émile Clapeyron only ten years after Carnot published his *Reflexions*. The only graphical representation Carnot used is the picture on slides 29-30.



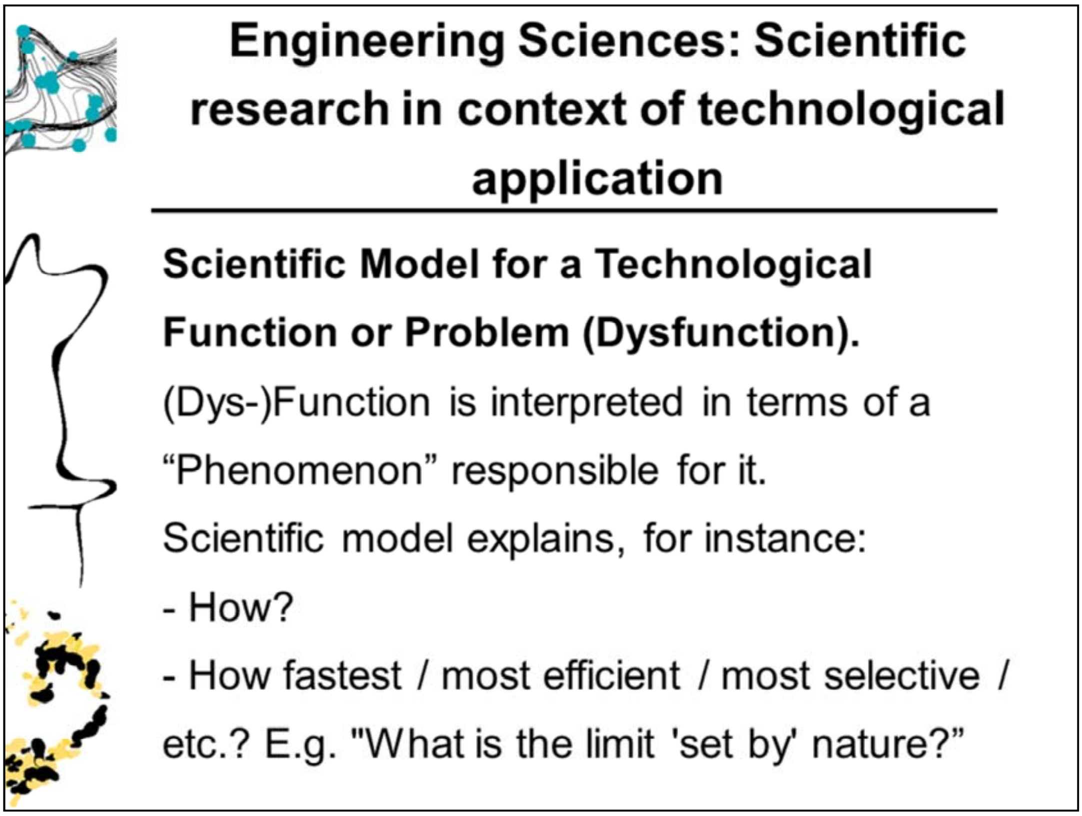

*III. Articulating the epistemic aim*

The engineering sciences usually start from questions related to practical problems and applications, such as, the problem of how the functioning of a device can be improved. The problem that Carnot got interested in was how to improve the performance (or efficiency) of heat engines. In his *Reflexions*, he writes that,

> "The study of these engines is of the utmost interest [because] their importance is immense, and their use is increasing daily." (ibid p.

Carnot was not interested in the "trial-and-error" approaches familiar to engineering of his days. Instead, he aimed at a theoretical answer to a fundamental question about the performance of heat engines:

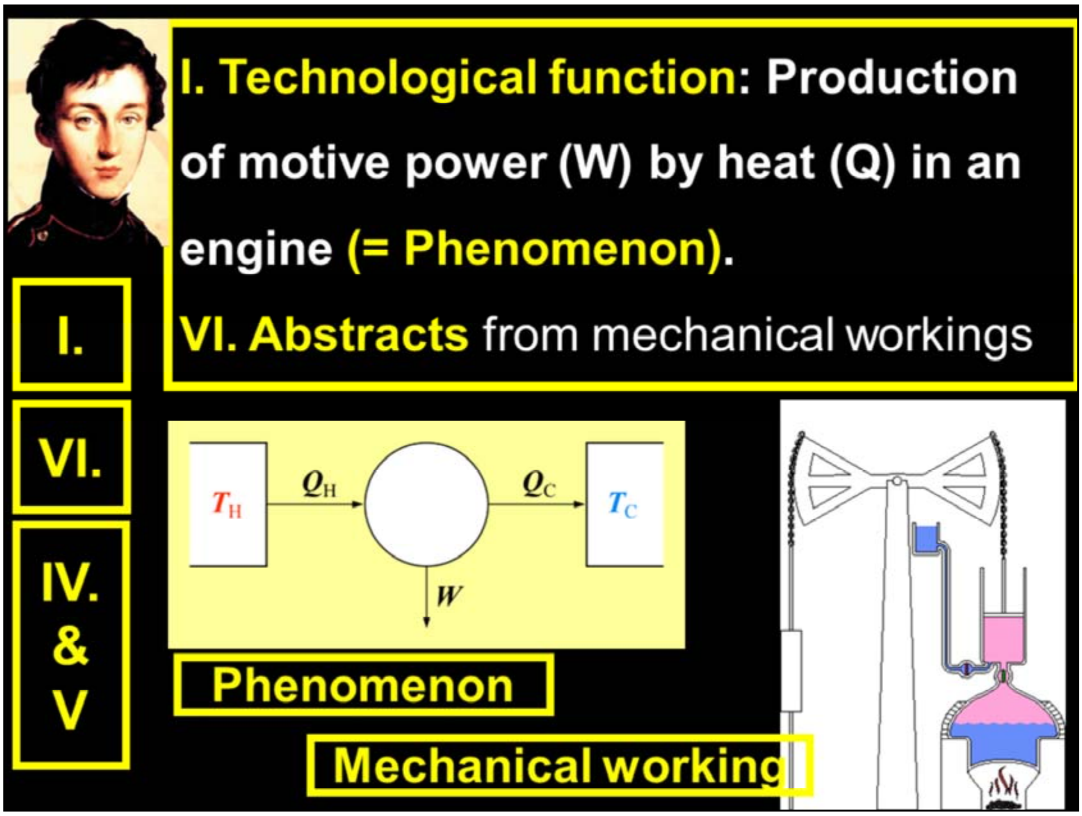
> "The question whether the motive power of heat [i.e. the useful effect that an engine is capable of producing] is limited or whether it is boundless has been frequently discussed. Can we set a limit to the improvement of the heat-engine, a limit which, by the very nature of the things, cannot in any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




**Epistemic aim common to the engineering sciences**

Carnot's fundamental question ("Can we set a limit to the improvement of the heat-engine, a limit which by the very nature of things, cannot be surpassed?") illustrates a kind of general *epistemic purpose* common to the engineering sciences, to wit, finding out the fundamental limit to the improvement of the desired (or to the minimizing of the undesired) capacity of a technological artefact via theoretical understanding of the very nature of this capacity.

For this purpose a model of an ideally functioning technological artefact is constructed, which enables, but also limits scientific reasoning about possible, or hypothetical, interventions with the real technological devices (e.g. the real heat engines). Consequently, the Carnot model can be conceived of as an epistemic tool for reasoning about why, on the one hand, certain losses cannot be avoided, and how, on the other hand, one could minimize these losses of the heat engine. Note that from this perspective the aim of scientific modelling is not primarily that of *representing* some real target-system more or less accurately, but rather producing an epistemic tool (which represents a hypothetical device, the ideal heat engine) to be used for meeting some specific epistemic aim.




*Step I. Discerning the target phenomenon*

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

How is the phenomenon then (re)conceptualized? Generally, developing a scientific model for a technological artefact such as the heat-engine, involves conceiving of its functioning in terms of particular *physical phenomena* that produce its proper or improper functioning. (This, by the way, shows also that the engineering sciences proceed in theorizing in the same way as the physical sciences). Hence 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)

Note that the diagram with T, Q and W is a modern representation of the target phenomenon, not invented by Carnot.

*Step IV. Abstracting from mechanical workings of the steam engine.*

Hence, Carnot conceived of the functioning of the heat-engine, not primarily in terms of its mechanical working , but as a device that produces *motion by heat*, which is the target phenomenon to be modelled.

*Step VI. Relevant and measurable variables.*

By means of this abstraction, also some of the variables become obvious that are relevant for the production (and the scientific understanding) of the target phenomenon, such as temperature and pressure in the process, the amount of work produced (W), amount of heat consumption (Q), ..

It should be noted that not all these variables are actually measurable. Temperature, for instance, was not measurable by then, and also the amount of heat could not be measured as it requires the measurement of temperature. Later in the history of science, the amount of heat was understood as the amount of caloric (e.g. the amount of caloric in a substance at a specific temperature). One unit of Caloric, for instance, is defined as the quantity of heat required to raise the temperature of 1 gram of water by 1°C (which is equal to 4,18 Joules). It was through the work of Carnot and other researchers in those days that the measurement of temperature could be developed (also see additional notes below).

**Thinking as a researcher: The importance of measurements and measurement techniques in the construction of scientific theories.**

[Some thoughts beyond Sadi Carnot. It aims to explain why step IV and V of the B&K theory are very important].

Usually, textbooks do not explain the crucial role of measurement instruments and experimental techniques in the construction theories. However, how a theory is actually constructed largely depends on what can be measured and which experimental techniques and manipulations with the system (or target phenomenon) under study are possible!

As a consequence, your understanding of theories and all kinds of equations derived in a theory (such as in thermodynamics and E&M) may improve if you figure out which variables can be actually measured, and how the values of variables that can not be measured directly, are derived from measurements by means of the equations of the theory.

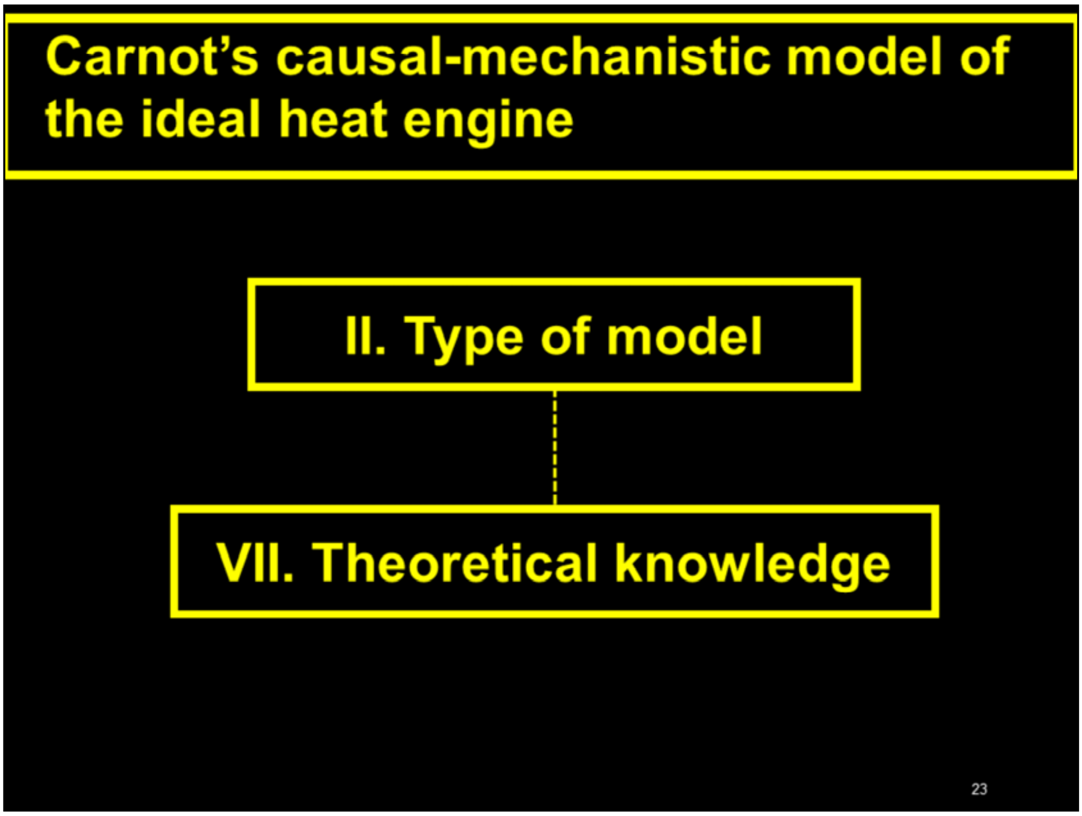
For instance, from textbooks it is not always clear why there are so many equations in thermodynamics

[e.g. see http://en.wikipedia.org/wiki/Heat_capacity and

http://en.wikipedia.org/wiki/Table_of_thermodynamic_equations].

And why are there all these different kinds of energy (Gibbs energy, free energy, enthalpy, etc.). The answer to this question becomes quite straight forward if you consider (1) what can be actually measured, and (2) the kinds of relevant conditions and variations possible in thermodynamic systems. Ad (1) Crucial to the understanding of thermodynamics is recognizing that the heat or energy (energy change or energy content) cannot be measured directly ! Currently, this is still the case – although, of course – measurement techniques have been improved and extended enormously – but still: Energy (and heat) is always measured indirectly, through temperature measurements together with the measurement of weight and/or volume of a substance (and at varying conditions). In standardized experimental procedures, then, the heat capacity of a substance can be determined at different conditions (such as, $C_V$ at constant volume, and $C_P$ at constant pressure). Ad (2) Below, the relevant, controllable conditions in the ideal heat engine are developed, such as 'heating a gas at constant temperature', or at constant volume or at constant pressure.

Summing up. In general, when aiming to understand a research project or scientific field, it is recommended to look for what is measurable, and how the variable is measured (directly or indirectly), and which aspects can be manipulated in experimental or technological procedures affecting the measurable variables. This search is what step IV and V of the B&K theory point at.




So far, we have some ideas on (I) the target phenomenon to be modeled, (III) the epistemic aim of the model, and (IV, V) the measurable variables. How does Carnot proceed in the modeling of the target phenomenon such that it will meet the epistemic aim? The question is (loosely phrased) 'to explain and determine the limit set by nature as to how much motive power is produced from heat in a heat engine'.

*Step II. Type of Model*

Carnot initially imagines how heat produces motive-power in terms of a causal-mechanistic process. Hence, he sets-off to construct a causal-mechanistic model of the target phenomenon. Thus, the starting point of Carnot's modeling tour is the formulation of the target phenomenon in terms of heat that 'somehow' *causes* the production of motive power.

*Step VII. Articulating and using theoretical knowledge.*

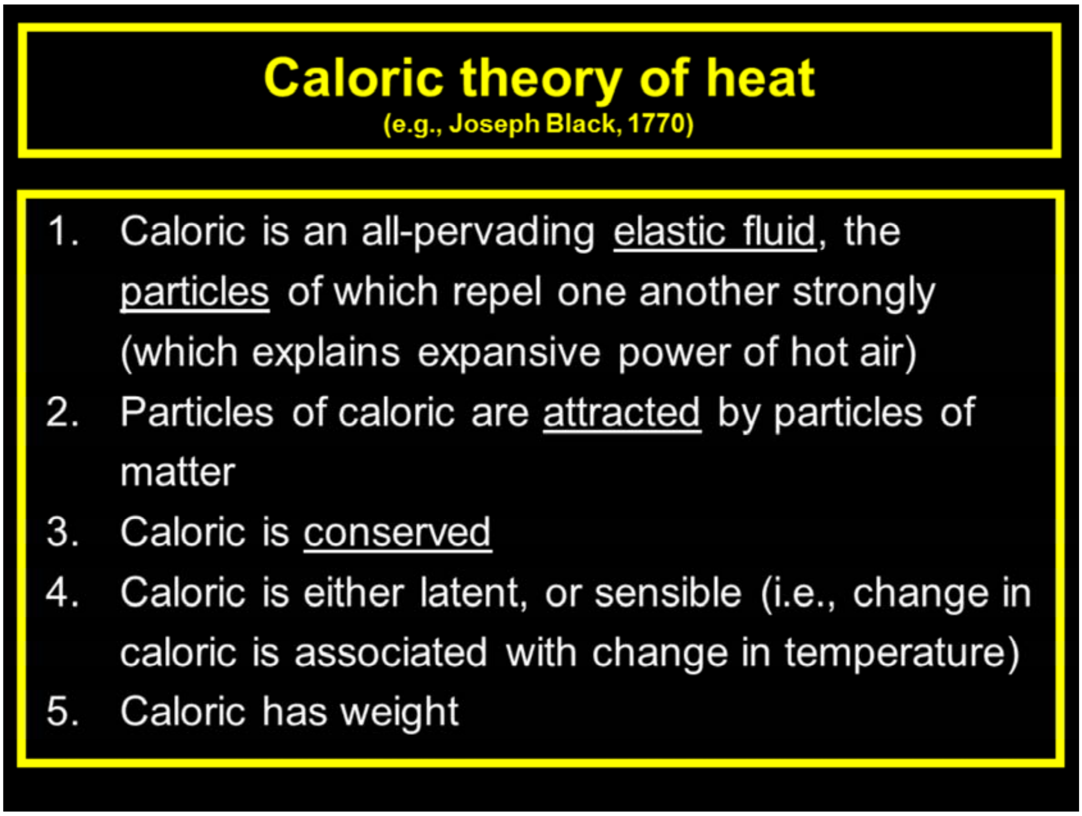
Developing the causal-mechanistic model involves the use of theoretical knowledge of those days, namely, the caloric theory of heat. The nature of heat, in Carnot's days, was conceived of as a material fluid called caloric (see next slide).

Carnot's new scientific conception of how heat produces motive power can be summarized as follows: Motive power is produced by *transfer* (i.e., by *transportation* rather than by *transformation*) of heat from a hot to a cold body:

> "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*. It is due, in other words, to a restoration of the equilibrium of caloric after that equilibrium has somehow been disturbed ..." (ibid p. 65, his italics).

Note: Carnot's presupposition of the conservation of heat was in accordance with the caloric theory of heat of his days. It was replaced by the idea of the conservation of energy (which is the first law of thermodynamics) by the work of his successors such as Thomson (also see Chang, 2004).

Carnot's approach is an illustration of how scientists think. As you will see below, it involves HD reasoning and the use of analogies. By using an accepted theory (the caloric theory of heat), Carnot constructs an explanation for how heat produces motive power. This explanation should explain (that is, the observed phenomena can be deduced from it), and it should be coherent with relevant empirical knowledge.




**VII. How researcher construct models: Using existing theory:**

Carnot does not spell out his notion of caloric in *Reflexions.* A generally accepted account of caloric in those days was presented, for instance, by Dalton (1842), who stated:

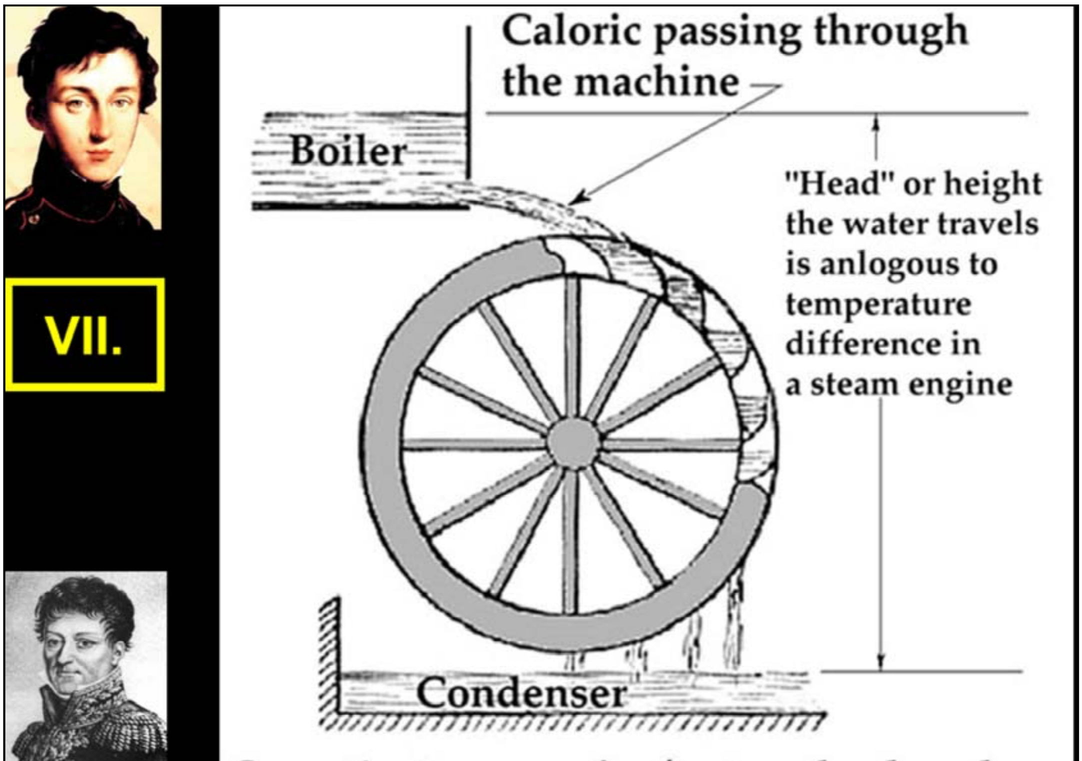
"The most probable opinion concerning the nature of caloric, is, that of its being an elastic fluid of great subtility, the particles of which repel one another, but are attracted by all other bodies. ..." (Dalton, 1842, p.1; first edition, 1808).

Notes:

Our basic reconstruction of Carnot's conception of heat has been taken from Clausius' (1865, 1899) *Memoirs on Carnot*.

Kuhn (1958) argues that Carnot followed Poisson who took from the caloric theory only the hypothesis that the heat content of a gas is a state function (which means that the heat content of an amount of gas is fully determined by the pressure and the temperature of the gas), and further, that at fixed pressure the caloric content is proportional to volume. Accordingly, Poisson developed a formula for the dependence of heat capacity on pressure. These assumptions and formula enabled Carnot to carry out calculations in the empirical part of his *Reflexions* (starting on ibid p. 78).

This concept of caloric is enriched with the idea that temperature is the density of caloric. In a further theoretical elaboration, it was postulated that caloric exists in two different states: sensible and latent. In its free state, caloric was conceived of as sensible, being able to affect the thermometer and our senses, whereas in its latent state, caloric is combined with matter and deprived of its characteristic repulsive force, thus being unable to effect the expansion of thermometric substances. This refinement of the caloric theory allowed for explaining e.g., that addition or withdrawal of (latent) heat causes a change of a state (e.g., melting, freezing, boiling, condensation, etc.) without a change of temperature (cf. Chang, 2003 and 2004).



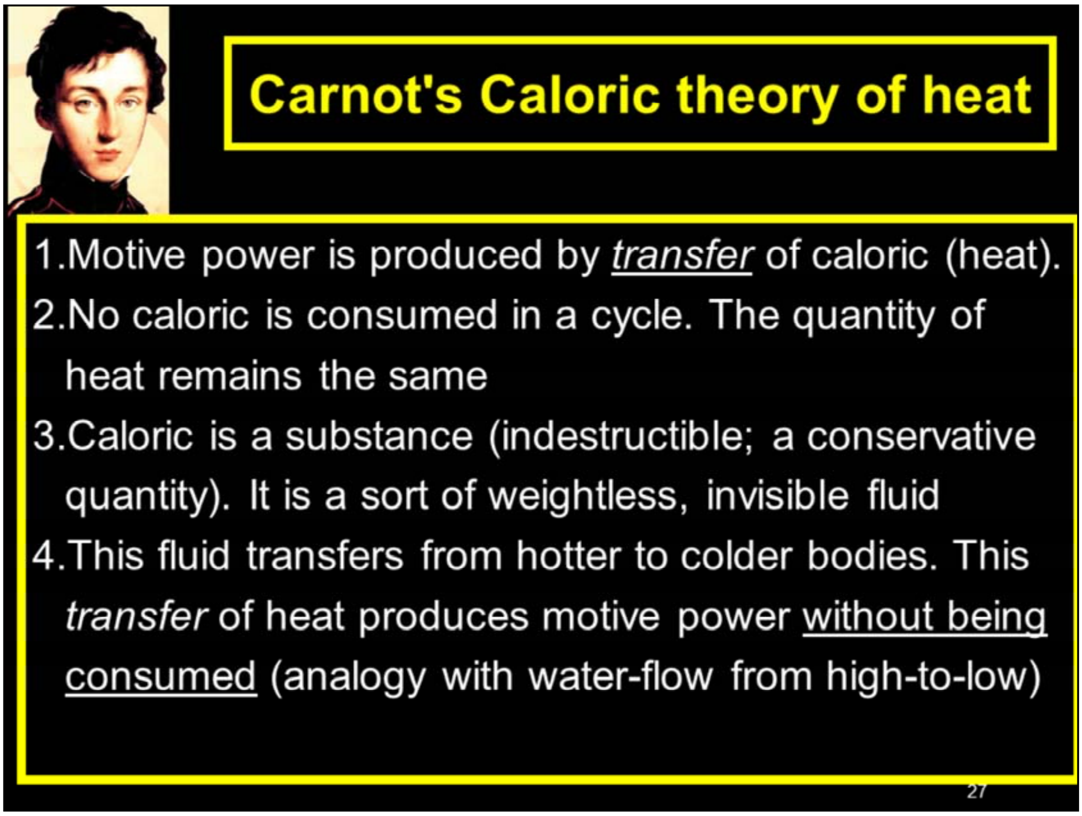
Carnot's steam engine/waterwheel analogy

**VII. How researchers think and construct theoretical ideas: Reasoning by analogy.**

Carnot's conception of how heat produces motive power involved an analogy to how water-wheels produce motive power, as proposed by his father, Lazare Carnot, who had worked on a theoretical understanding of their efficiency. According to this analogy, heat (caloric) spontaneously flows from high to low temperature, similar to how water flows from high to low levels, producing motive power (the turning of the water-wheel, *c.q.*, the movement of the piston of a heat engine). Similar to water-flow, caloric-fluid flows from a hot to a cold body without being transformed or consumed itself. This conception implies that no heat is consumed in a cycle of the heat engine (in which gas is heated, then expanded – producing motive power –, cooled, compressed, and heated again); *i.e.*, the *quantity* of heat in this cycle remains the same.

In this way, Carnot developed a scientific conception of the target phenomenon by bringing it under a conception of how caloric produces motive power thus making it scientifically accessible.

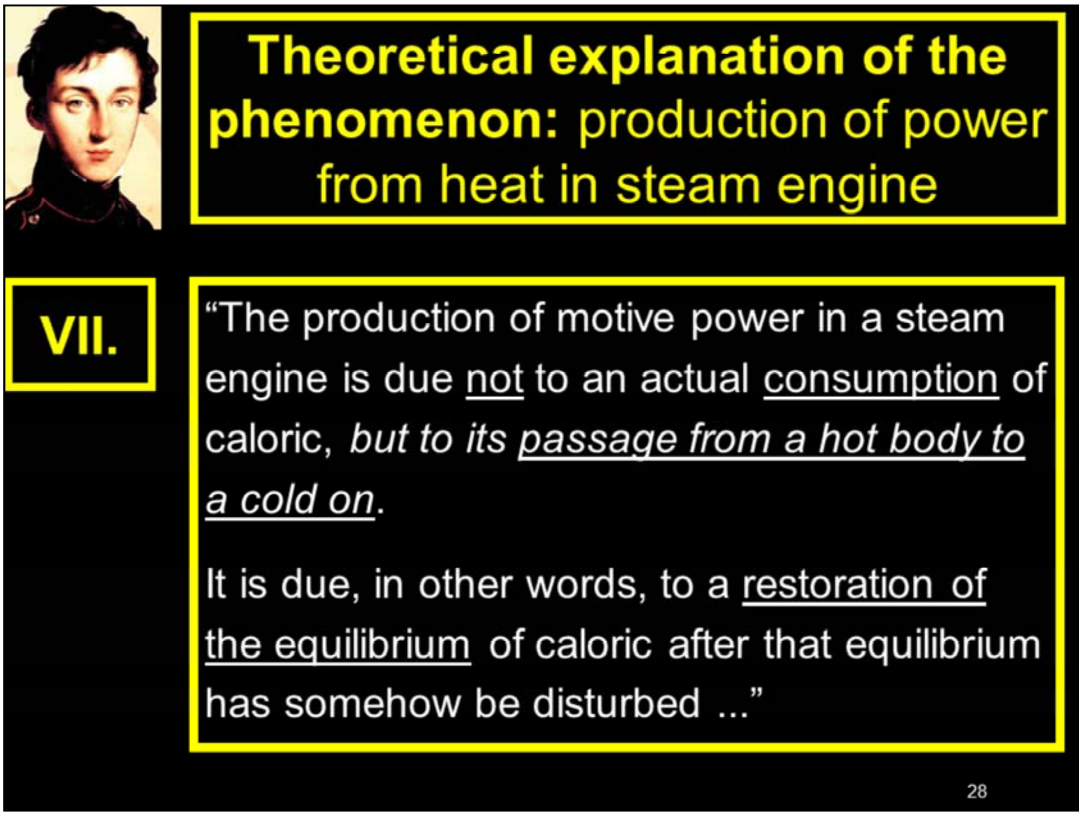
It can be easily imagined that also the efficiency of a water-wheel is much lower than the efficiency that is possible theoretically.




**VII. How researchers think and construct theoretical ideas:**

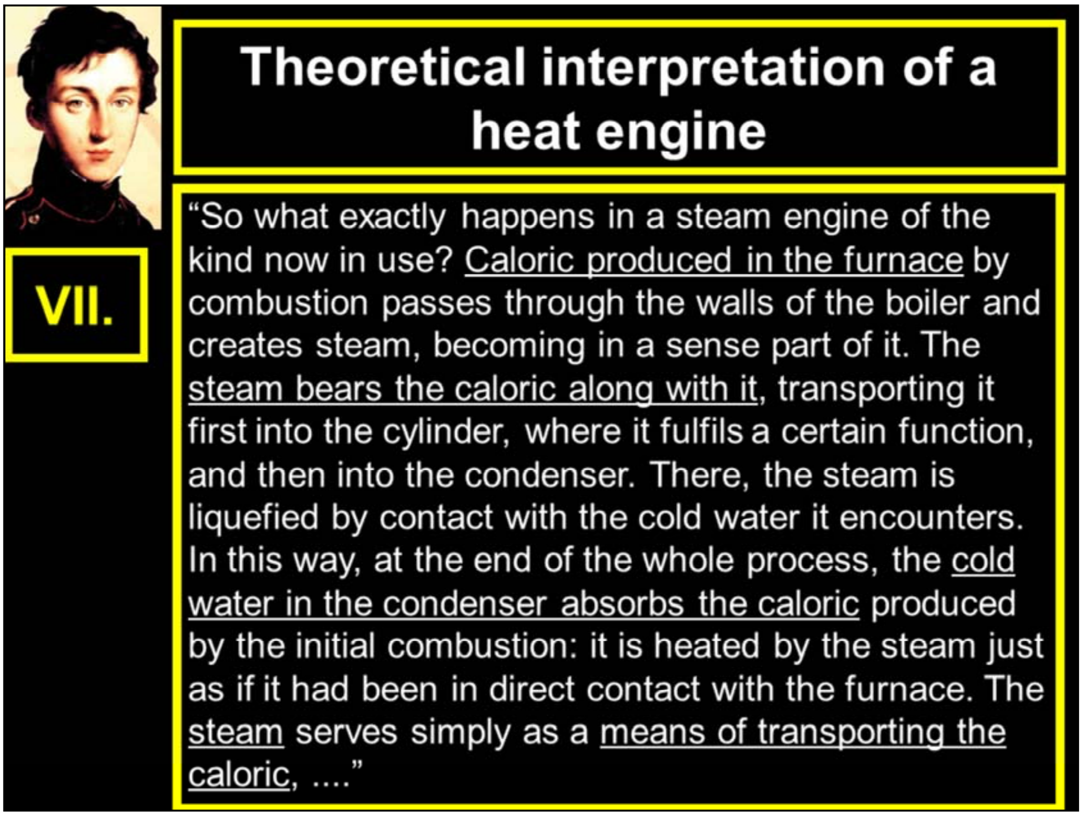
The result of Carnot’s reasoning: This slide presents an outline of Carnot’s explanation of how heat produces motive-power The explanation is cast in terms of the purported properties and behaviour of caloric (heat).

Clearly, this explanation does not meet the epistemic aim of the model. Nevertheless, the explanation so far enables developing the model further.




**VII. How researchers apply theoretical ideas:**

At this point, Carnot applies his caloric theory of heat in (a preliminary) explanation of the production of motive power in a steam engine.




**VII. How researchers think and construct and apply theoretical ideas:**

Carnot applies his caloric theory of heat for explaining the production of motive power in a steam engine. That is, he can now explain how the steam engine produces the target phenomenon. Recall what was said earlier: often, phenomena are technologically produced, and the engineering sciences also want to explain *how* the phenomenon (that is of technological interest) is technologically produced. That is what happens on this slide.

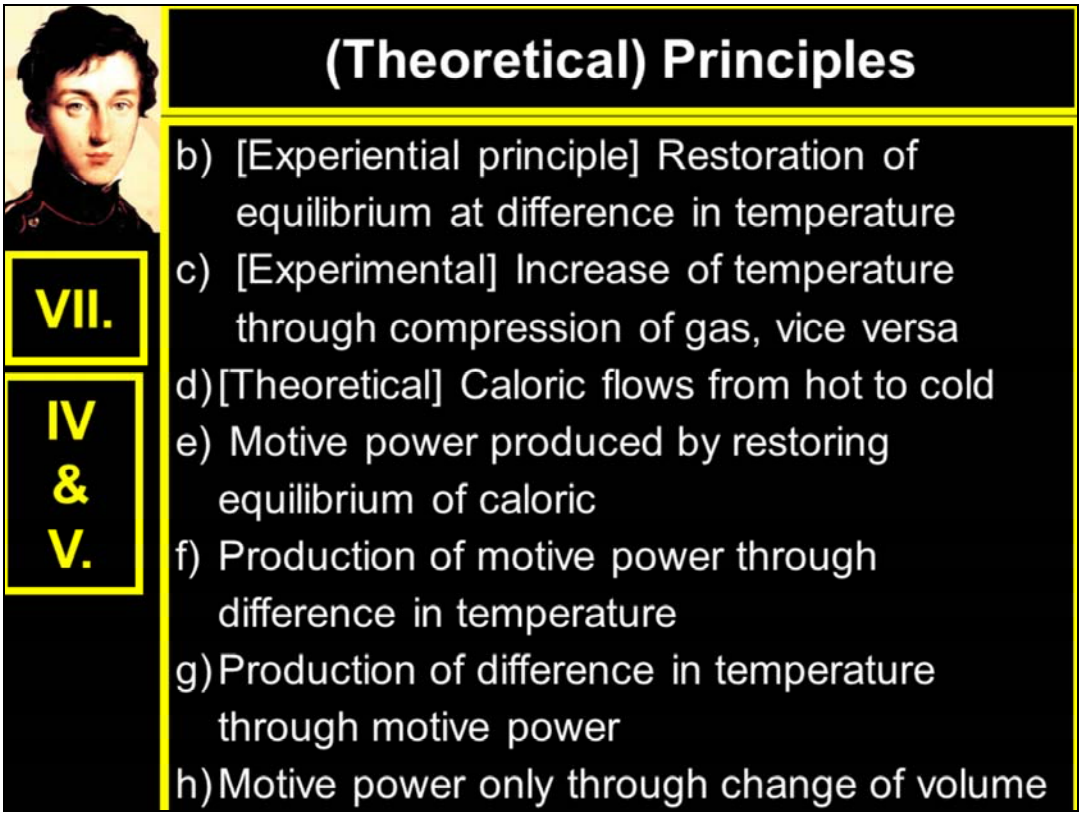
Conceiving of the target phenomenon in terms of transporting caloric, which is supposed to be carried around by steam cycling through the engine, enables Carnot to explain the functioning of the steam engine:

> “So what exactly happens in a steam engine of the kind now in use? Caloric produced in the furnace by combustion passes through the walls of the boiler and creates steam, becoming in a sense part of it. The steam bears the caloric along with it, transporting it first into the cylinder, where it fulfils a certain function, and then into the condenser. There, the steam is liquefied by contact with the cold water it encounters. In this way, at the end of the whole process, the cold water in the condenser absorbs the

> caloric produced by the initial combustion: it is heated by the steam just as if it had been in direct contact with the furnace. The steam serves simply as a means of transporting the caloric, ... we are considering how the movement of the steam is put to use." (Carnot, 1986, [1824], p. 64)

In other words: (1) We already knew that the target phenomenon (producing motive-power from heat) is responsible for the functioning of the steam engine. (2) Here, the target phenomenon responsible for the functioning of the steam engine is interpreted in terms of Carnot's caloric theory of heat such that the resulting description explains the functioning of the steam engine.

Still, this explanation of *how* the steam engine produces the target phenomenon, does not meet the epistemic aim of the model – but again, the model at its current state enables developing it further.




**Introduction of propositions and principles that relate the transport of heat (caloric) and production of motive power to relevant (measurable) parameters:**

Carnot proceeded in his modelling endeavour by introducing propositions and principles that relate the conception of the transport of heat (caloric) and the production of motive power, to relevant (measurable) parameters such as temperature, volume, and compression or expansion of the gas in the steam engine. In this way he also tied the scientific aspects that he has incorporated into the model so far, to data that can be observed or measured in the real systems.

How does he get these principles?

Some of these principles are definitions (e.g., a), others are experiential or experimental (e.g., b, c), and yet others theoretical (e.g. d, e, f, g, h). His development of these propositions and principles is reconstructed and summarized in the list below (ibid pp. 64-67):

Firstly, Carnot presents a definition of heat engines that draws on his conceptualization of it:

a. A <u>definition</u>: The heat-engine is any engine that is driven by caloric.

He articulates also an experiential principle, which is important for the consecutive modelling exercise:

b. Equilibrium restores wherever a difference in temperature exists.

Additionally, there is an experimentally well-known fact that:

c. The temperature of gaseous substances rises when they are compressed, and falls when they are expanded.

d. A <u>theoretical principle</u> is that 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,

e. in steam engines motive power is produced by the re-establishment of the equilibrium of caloric, not by consumption of caloric, And

f. whenever there is a difference in temperature, motive power can be produced,

while the converse is also true, that is,

g. 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.

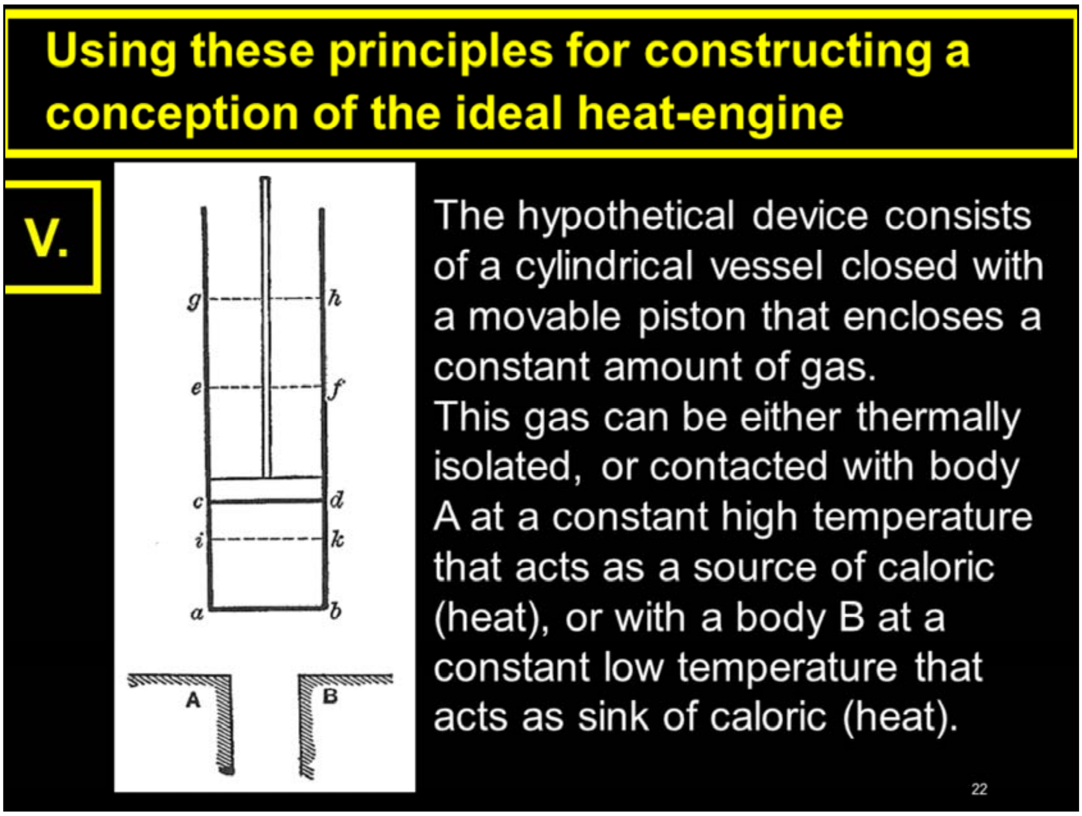
From these principles Carnot infers “an obvious” principle that

h. heat can only be a source of motion in so far as it causes substances to undergo changes in volume or shape.

At this point, Carnot has build into the model several principles by drawing on some experiential or experimental knowledge and on theoretical ideas. He thus created a new way of imagining what is going on in heat engines.

Note:

One should keep in mind that the measurements of several variables crucial to Carnot’s model, such as temperature and (latent) heat, were not at all straightforward. Chang (2004) argues that the measurement and the conception of temperature had not been established in those days. To the contrary, Carnot’s ideal heat engine played an important role in conceptualizing temperature such as how to conceive of a measure of one degree (“absolute” temperature) and how to conceive of measuring it.




**Using these principles for constructing a conception of the ideal heat-engine**

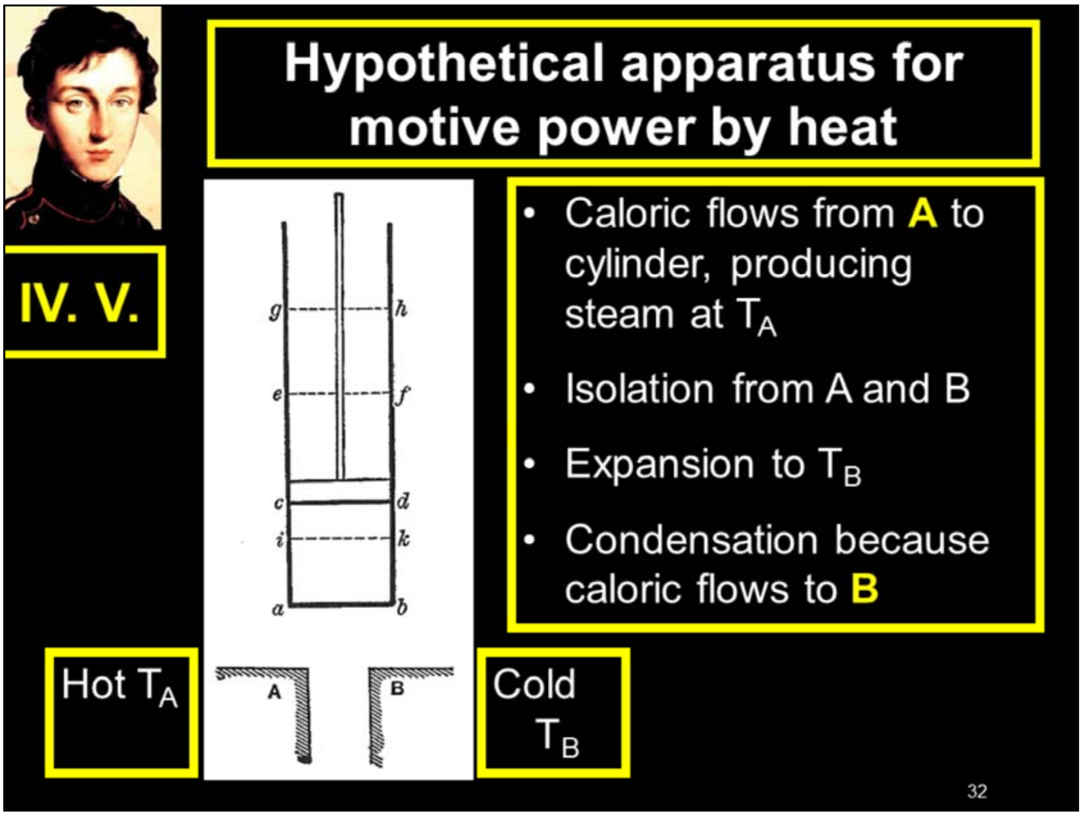
A simplified conception of the real heat engine consists of a furnace, a boiler, a steam containing cylinder closed with a movable piston, a condenser, and a reservoir of cold water.

The explicitly articulated principles (a-h) of the model together with this simplified conception of the steam engine enabled Carnot to imagine a hypothetical device that produces motive power by heat. This model functioned as an epistemic tool that guided and constrained its further development.

To start with, Carnot asked the reader to "imagine" two bodies, A and B at different constant temperatures $T_A$ and $T_B$ ($T_A$ being higher than $T_B$ ), to which heat can be added or from which it can be taken away without effecting any change in their temperature. A and B will act as two infinite reservoirs of caloric.

Accordingly, 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 body A at a constant high temperature that acts as a source of caloric (heat), or with a body B at a constant low temperature that acts as sink of caloric (heat).




Next, Carnot envisaged the operation of this hypothetical device as consisting of three operations (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”:

> (1) 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.
>
> (2) 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. [use of the principle g].
>
> (3) 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. (See ibid pp. 67-68).

## Introduction of new concept: *reversible process*

- For closing the cycle, liquefied steam at temperature B must be brought back to temperature A:
- Carnot introduces notion of 'reversible' processes by which he assume that operations (such as 1, 2, 3) 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".
- Carnot thus conceives of how the steam in the cylinder can brought back to its initial state in order to achieve a closed cycle.

33

*VII. Still another theoretical invention.*

**Introduction and use of an abstract concept: reversed processes**

However, by imagining the operations described in 1, 2, 3, only half of the cycle through which the hypothetical device must go, has been constructed. Closing the cycle requires that the "liquefied steam" at temperature B (in 3) is brought back to temperature A. This could easily be achieved by heating the "liquefied steam" to temperature A, as it may happen in a real heat-engine. However, at this point, Carnot made a brilliant conceptual leap by introducing the idea of a *reversed* process. Carnot stated 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 conjured up a sequence of processes that bring about a closed cycle, which is achieved by reversing the process so that the steam in the cylinder is brought back to its initial state.

We can easily follow Carnot in reasoning on an abstract level, claiming that operations 1, 2, 3, could possibly be reversed. However, what is remarkable about his conception is that this reversal does not draw on concrete experiential or experimental knowledge. In contrast, experiential and experimental knowledge of that time would have hindered any such reasoning, for it was not easy to imagine, for instance, that steam could be formed from water at temperature B by a cold body at temperature B (which is what actually happens in refrigerators). The introduction and use of this concept is a good example of how creative reasoning works. Such reasoning is made possible by bringing knowledge that has been systematically and explicitly brought together in the model under an abstract concept (reversed processes), leading in turn to new conceptions (forming steam at a low temperature by the transfer of caloric to it).

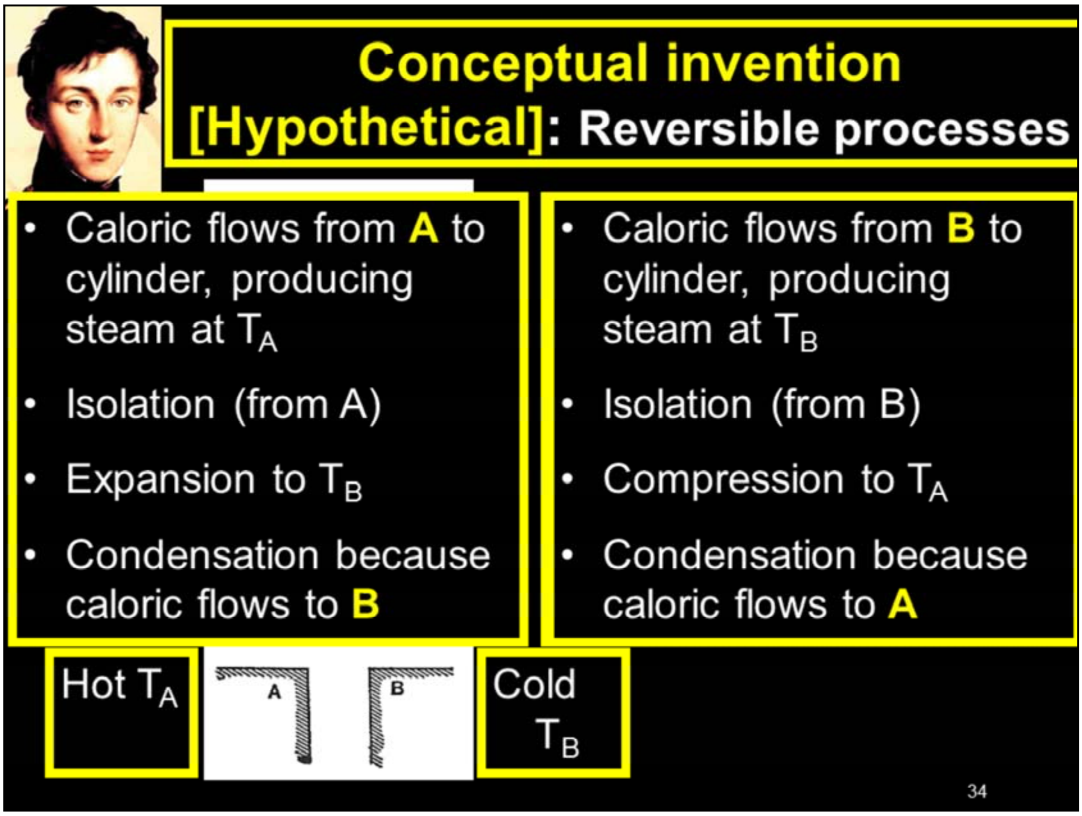
Nevertheless, the *hypothetical* idea of the reversible process raises the question of why we should believe that it is *physically* possible as well. Indeed, in order to explain how this would work physically, the conception of the reverse process needs to be fleshed-out much further, which is what happened in Carnot's further modelling.

The imagined possible operations (1, 2, 3, and reverse) guided Carnot in constructing a closed cycle that produces the maximum amount of motive power. First, Carnot used the notion of the reversed process to imagine a cycle in which in the first sequence of operations (1, 2, 3), motive power is produced and at the same time caloric is transferred from body A to body B, while in the reverse operations, exactly the same amount of motive power is expended and caloric returns from B to A. In this cycle no net motive power is produced, neither is there any net transfer of caloric from A to B. Carnot then argued that if it were possible to make caloric to yield a greater amount of motive power in the first sequence (1, 2, 3), we should have a case of motive power being created in unlimited quantities without the consumption of caloric, which contradicts the idea that perpetual motion is impossible for mechanical processes. By this reasoning, Carnot showed that in order to produce net motive power in a closed cycle, there must be a transfer of heat from A to B in a cycle. (ibid. 69)

Secondly, this idea of a closed cycle guided in specifying the performance (efficiency) of the hypothetical device as the ratio between the quantity of motive power developed in a complete cycle of operations and the amount of heat transferred from A to B. The motive power developed is defined as the product of the volume and the difference of its pressure at the expansion of the gas (sequence 1, 2, 3) minus this product at the compression of the gas. The total amount of heat needed is the amount of heat transferred from A to B (ibid. 98). The motive power developed is defined as the product of the volume and the difference of its pressure at the expansion of the gas (sequence 1, 2, 3) minus this product at the compression of the gas. The total amount of heat needed is the amount of heat transferred from A to B (ibid. 98).

Note:

Clearly, the transfer of heat could not be measured directly. In his actual calculations, Carnot argues: “As for the heat which is used – that is, the heat transferred from A to B – this quantity is clearly that which is required to convert the water into steam...” (ibid., 98). Note that the calculation of the efficiency in modern thermodynamics – which has abandoned the caloric theory of heat – uses the consumption of heat (i.e., the difference between the amount of heat entering and leaving the device) rather that the amount of heat that is transferred from body A to B.




Summary of operations involved in the closed cycle of the hypothetical device:

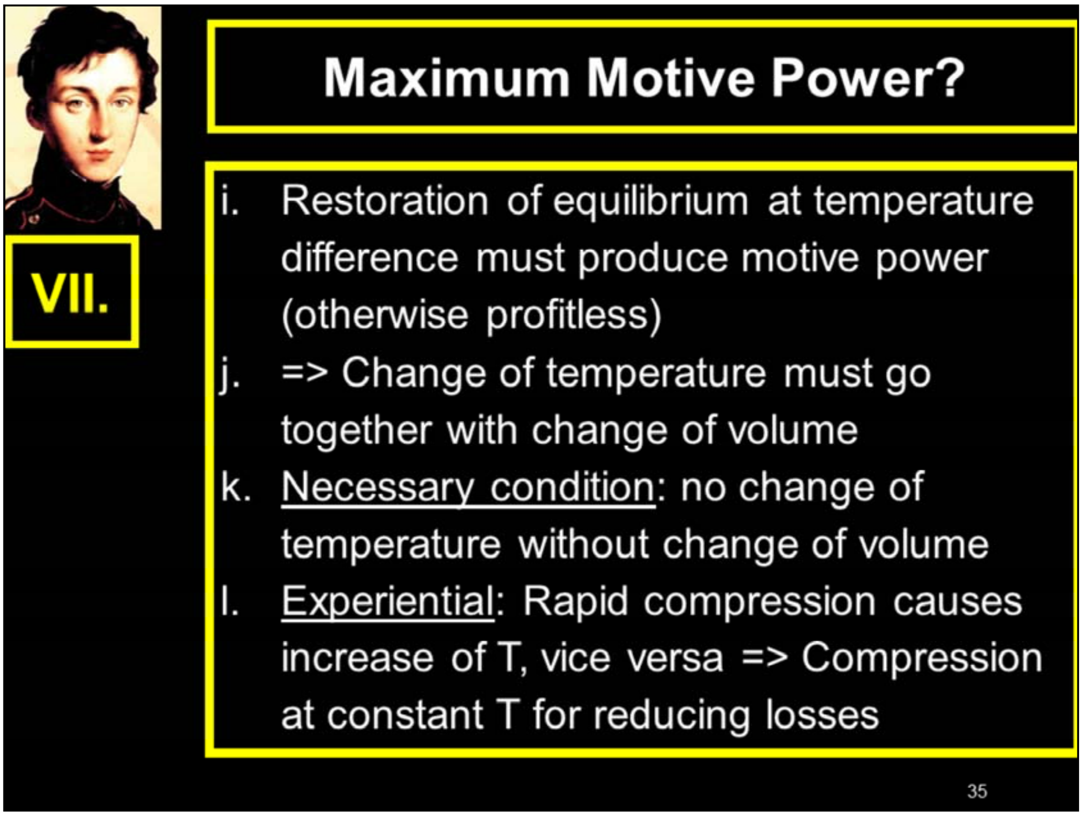
- Caloric flows from **A** to cylinder, producing steam at $T_A$
- Isolation (from A)
- Expansion to $T_B$
- Condensation because caloric flows to **B**

Reverse:

- Caloric flows from **B** to cylinder, producing steam at $T_B$
- Isolation (from B)
- Compression to $T_A$
- Condensation because caloric flows to **A**

- Caloric flows from **A** to cylinder, producing steam at $T_A$
- etc

- Caloric flows from **B** to cylinder, producing steam at $T_B$
- Etc.




**The model in its current state is an epistemic tool for scientific reasoning towards the Maximum Motive Power:**

Carnot's next question was how the *maximum* amount of power could be obtained, and what "maximum" in this context means. The model of the hypothetical device in its current state suggested that it meant minimizing the causes of the loss of heat. Further development of the model thus required accounting for the possible causes of loss of the hypothetical device. Again, the model in its current state, in particular the formerly stated principles (a-h), enabled Carnot to develop some additional principles that explained losses (and the avoidance of losses).

*VII. Deriving principles for producing the maximum amount of motive power, i.e., principles for avoiding losses*

These principles are the following (ibid p. 70):

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.

Reflecting on this latter point, Carnot concluded:

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

Hence:

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

However:

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

What becomes obvious as one looks at these latter principles (i-l) is that Carnot had to construct a cycle which avoided that a change of temperature was not accompanied by a change of volume (j), and which also avoided the occurrence of rapid compression or expansion (l).

## Operation of the Ideal Heat Engine

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

36→

**Constructing the ideal heat-engine such that losses are minimized**

So far, Carnot' s model encompassed a hypothetical device (which consisted of a cylindrical vessel closed with a movable piston that encloses a constant amount of steam – in which the gas either can be (1) thermally isolated, which means that there is no transfer of caloric, or (2) contacted with body A at a constant high temperature that acts as a source of caloric [heat], or with a body B at a constant low temperature that acts as sink of caloric [heat] – which goes through cycle 1, 2, 3, and reverse), as well as knowledge by which he could construct the possible operations (i.e., principles a-h), and knowledge about the causes of loss (i.e., principles i-l).

Carnot used this model as an epistemic tool for constructing a cycle that produces the maximum amount of motive power. That is, he used the model at this stage for constructing a hypothetical device called the ideal heat engine.

As has been illustrated, Carnot's approach entailed using the model for imagining different kinds of possible operations with the hypothetical device. The last step to take is to construct a hypothetical cycle that avoids losses, which, as he knew by now, had to be constructed in such a way that the problem of “restoring caloric profitlessly” was avoided by preventing that “changes in temperature occur that are not due to a change in volume”.

*VI. Simplification*.

In the further construction of the hypothetical device he decided to use gas instead of steam, which simplified the hypothetical device to the extent that the processes of condensation and evaporation in a cycle could be neglected.

*Model in its current state is used as an epistemic tool for constructing a cycle with minimal losses.*

Carnot imagined, for instance, how the temperature could be changed by withdrawing or supplying caloric without changing its volume. According to the principle j, this is an operation that causes loss, which therefore must be avoided in the ideal heat engine. Carnot argued that it would be equally possible to withdraw caloric during the process of compression in such a way that the temperature of the gas would remain constant, which implies that the rise of temperature that would be due to rapid compression (principle l) can be avoided. Likewise, if the gas is expanded, its temperature can be prevented from falling by supplying an appropriate quantity of caloric. (ibid., 72). We claim that imagining such operations results from using the model as an epistemic tool. Note that knowledge of such operations could by no means have been derived from mere experience with real steam engines.

By this way of reasoning, Carnot proposed a hypothetical cycle of four operations that is supposed to produce the maximum amount of motive force, arriving thus at the ideal heat engine. The description of the four operations of the ideal heat engine refers to the schema of the cylinder with piston that can be contacted with bodies A and B (see picture above in slide 29):

(1) The air is placed in contact with the body B. It is then compressed by returning the piston from its position *gh* to *cd*. During this process, the air maintains a constant temperature, since it remains in contact with B and gives up caloric to it.

(2) The body B is taken away, and the compression of the air is continued. Since the air is now isolated, its temperature rises. Compression continues until the temperature of the air reaches that of the body A, by which time the piston has moved from the position *cd* to *ik*.

(3) The air is placed once again in contact with the body A, and the piston returns from *ik* to *ef*; the temperature remains constant.

(4) A is removed, so that the air is no longer in contact with any body that can act as a source of caloric. But the piston continues to move, rising from the position *ef* to *gh* The air expands without absorbing caloric, and its temperature falls. Let us *suppose* that the temperature continues to fall until it is equal to that of B, whereupon the piston stops at the position *gh*. (see ibid pp. 74-75).

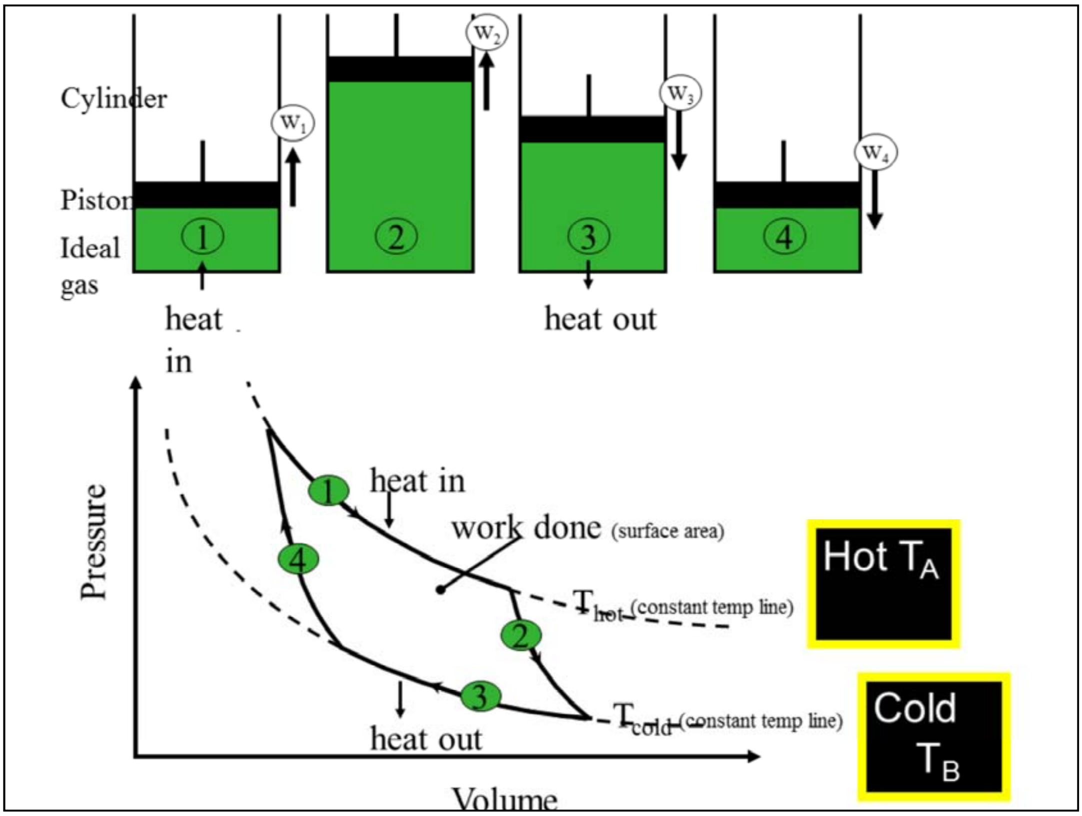
This description of the cycle drew, as we have seen, on the previously developed conceptions of possible operations. Hence, Carnot's model of (the operation of) a heat engine finally covered the epistemic aim, expressed in terms of the target phenomenon, different pieces of knowledge as presented in principles a-l, and the final formulation of the ideal heat-engine, which is a hypothetical device that is supposed to produce motive force at minimum loss (i.e., the maximum amount of motive force that can be produced by heat-engines).

## Carnot's model of the ideal heat engine

I. Phenomenon: Conception of the real heat-engine as ar abstract device that produces motion by heat.
II. Type of Model: Causal-Mechanistic
III. Epistemic aim: It must explain the theoretical limits of th performance of this device.
IV. Relevant properties: T, V, P, $C_V$ and $C_P$ of substance
V. Measurable: T, V, P, $C_V$ and $C_P$, but not caloric.
VI. Abstraction: Mechanics of machine, Gas versus steam
VII. Theoretical and empirical knowledge: Charles, Boyle.
VIII. Justification: Only reasoning and experience. No experimental tests!

To summarize the result of the analysis by means of the B&K theory of Carnot's modeling of the ideal heat engine as performed here. For the sake of clarity, it is kept very short and sketchy (which makes it a bit superficial and incomplete).

Note again that in those days, it was not possible to measure temperature (in step V and VI) as we do it now. Notes in the slides below explain this issue somewhat further.




***PV* diagram** representing the cycle of the ideal heat-engine. This diagram presents a well-known modern conception of the Carnot engine, which has adopted the idea of energy rather than heat (caloric). It uses representational tools, such as the P-V diagram, that were only developed by Carnot's successors.

*IV and V: Relating the model to the empirical data and producing new knowledge through it*

Carnot included in his model variables, such as the pressure and the volume of the gas, that hook the model to the observable or measurable world. This may suggest that in the remainder of his *Reflexions* (ibid pp. 78-112), Carnot aimed at testing the model by comparison of its predictions to empirical data. However, even if it were possible to build a device that resembles it (a gas-containing cylinder closed with a frictionless piston, alternately contacted to or isolated from the sources of heat), methods to quantify variables such as the temperature and the amount of heat (caloric) of gas had not been established.

*VIII. Testing the model*

In other words, in *Reflexions*, testing and justification of the model does not take place by the comparison of the outcomes of the model to real data, but only by its construction (i.e., along the lines of steps I-VII). This is not to claim that the results of models (i.e. the conclusions produced by using models as epistemic tools) are never put to empirical tests, neither that their justification merely consists of how they are constructed. Moreover, as we have seen, empirical findings are crucial for how models are constructed, and thus play a role in their justification. Undeniably, new empirical findings, but also new theoretical insights, may lead to revisions of (some aspects of) the model – indeed, this is what happened to Carnot's model when the caloric theory of heat was substituted.

Note:

Chang (2004) shows that the definition and the measurement of temperature had not been settled in Carnot's days. What is more, establishing the measurement of temperature meets many, often entangled, practical and theoretical challenges with the result that the development of the definition and measurement of temperature has been inextricably intertwined with the development of thermodynamics. Significant to our case is how Thompson used Carnot's conception of the ideal heat engine to define the interval of one degree of temperature (i.e., "absolute temperature") as the amount that would result in the production of a unit amount of mechanical work in a Carnot engine operating in that temperature interval (Chang, 2004, 182). Besides the fact that the ideal heat engine could not easily be operationalized, Thomson's idea was abandoned when Carnot's basic assumption concerning the conservation of the heat was rejected.

FIG. 131.—How Light and a Pinhole Form an Image.

One important question is whether Carnot was actually able to use the ideal heat engine as an epistemic tool for reasoning about the real heat engines thus producing new knowledge concerning them. In the remainder of his *Reflexions* (ibid pp. 78-112) Carnot indeed used the model in this way: for instance, he discussed variables that could affect the efficiency of the device, such as the working substance (e.g., heat or steam or alcohol), the temperature of the bodies A and B, and their temperature difference. In these discussions he related the model to actually available measured data and phenomenological laws, thereby producing new physical knowledge of gasses, presented in propositions such as:

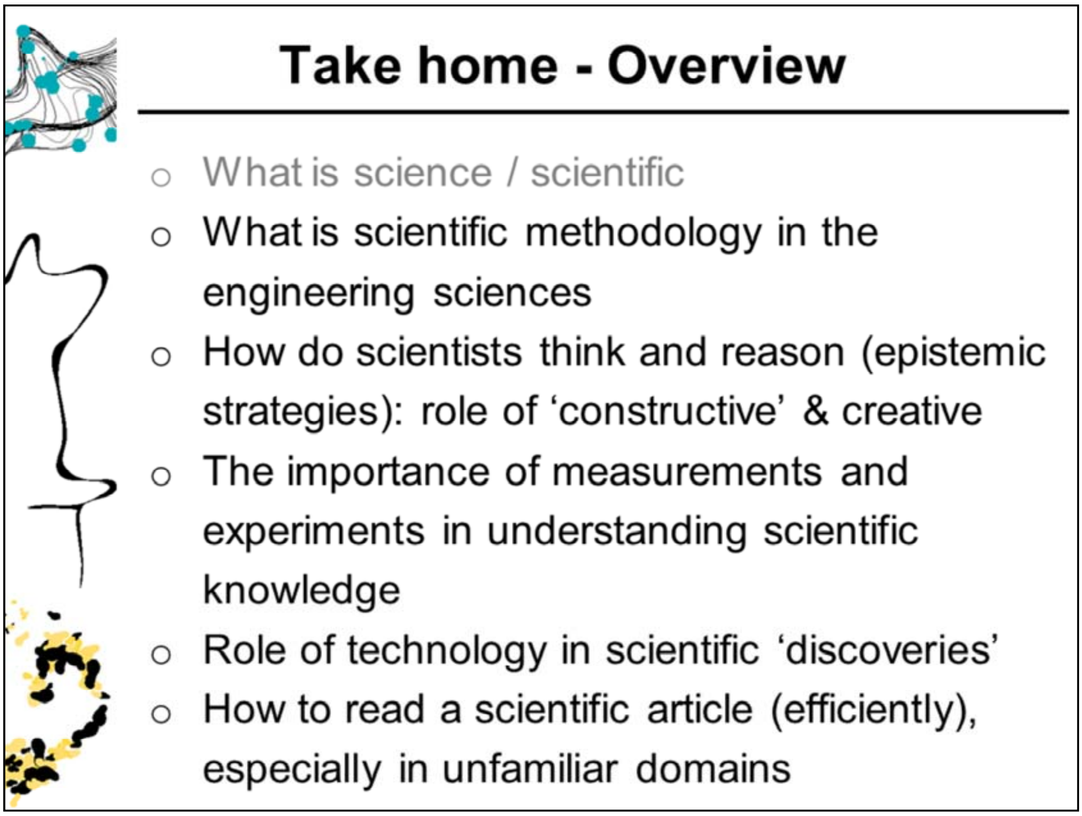
"The motive power of heat is independent of the working substance that is used to develop it. The quantity is determined exclusively by the temperature of the bodies between which, at the end of the process, the passage of caloric has been taken." (ibid., 76-77).

and

"The difference between the specific heats at constant pressure and the specific heat at constant volume is the same for all gases." (ibid., 80).

Besides finding out which factors affect the efficiency of the device, he also aimed to find ways for determining specific properties of gasses, in particular their specific heats (the amount of heat needed to raise its temperature with one degree at either constant volume or at constant pressure), as these data would allow for making calculations on, e.g., the efficiency.

Finally, Carnot used the physical knowledge of gasses thus developed, together with available quantitative data, for estimating the heat transfer in a cycle per unit of motive force, and hence the maximum efficiency of the ideal heat engine. In these examples, the model enabled the production of knowledge that was not already contained in it by the use of it as an epistemic tool for reasoning about empirical data (of gasses) towards new conclusions concerning the properties of gasses and heat engines, respectively.




**What have we learned about scientific methodology in the engineering sciences by this B&K analysis of Carnot's work?**

The aim of this analysis of Sadi Carnot's work was:

(1) To illustrate how a technological problem can be translated into a scientific research problem.

(2) To illustrate scientific modeling of (technologically relevant) phenomena produced by technological devices. To illustrate what it means to '<u>construct</u>' a scientific model.

(3) To illustrate the use of the B&K theory in analyzing how a scientific model (of a phenomenon, and for an epistemic purpose) is constructed.

(4) To illustrate what it means for a scientific model to be an epistemic tool (e.g., a tool for thinking about solving the technological problem).

(5) To show that difficult, 'abstract' (and unfamiliar) theories become easier to understand when understanding how they were constructed, in particular, how they draw on concrete observations, problems, measurements, instruments, experiments, and reasoning.

- <u>Is there something specific about the *engineering* sciences?</u> Yes! This example shows that the final theory (the model of the ideal heat engine) explains how an (idealized) technological device produces the (technologically relevant) phenomenon (i.e., converting heat to motive power). So, the theory abstracts away much of the concrete technological device, but still explicitly refers to (or, 'is about') the technology that produces the phenomenon.

- What *is* the model? First of all, it would be wrong to regard the PV diagram (slide 35) as *the* model (which is what people easily tend to do). This diagram is a convenient summary, but the full model also involves the principles and descriptions presented by Carnot. Secondly, the B&K theory puts emphasis on the *building* of a model, on the *modeling*. Building a scientific model means that different elements (those described in aspects I-VIII) are introduced and connected to a coherent whole, to a coherent kind of story. As you have seen in this analysis, this also means that at each stage of the modeling the gathered elements are already used 'as epistemic tools' for making the next step in the modeling. So, the model develops in different stages. At each 'intermediate' stage it can be called a model – however, at those intermediate stages it did not meet the epistemic aim of the model. Nevertheless, the model at its intermediate stages was used all the time as an epistemic tool for the further development of the model. In the analysis, this has been indicated.
- How did Carnot test or justify his theory (aspect VIII in the B&K theory)? In this analysis we saw that Carnot 's scientific approach is very much based on scientific reasoning that is both logical, rigorous and creative (also see slide 39)! He used experiential knowledge and empirical knowledge (e.g. from Boyle's experiments) in constructing the model, but he did not test it by means of experiments. Therefore, his approach shows us an important feature of scientific modeling: much of the justification of the model is already in how it was constructed. Would this mean that 'anything goes'? No. Why not? Because other epistemological criteria play a crucial role in the modeling, such as coherency with relevant theoretical, experiential and empirical knowledge (which encompasses empirical adequacy regarding existing knowledge) and internal coherency and logical consistency.
- Carnot used a theoretical concept (caloric) that was rejected shortly after. Does this undermine his theory? It undermined his caloric theory of heat, but not the model of the ideal heat engine (that is, not his explanation of the highest efficiency of heat engines).

  The notion of caloric was rejected, not because it was discovered that caloric does not exist, but because the concept led to all kinds of contradictions in thought-experiments, and incoherencies with experience. For instance, it was not possible to explain why an object heats when rubbed; for, this experience would imply that caloric particles were *generated* by rubbing, which is at odds with the conservative character of caloric particles!

  Problems with the concept of caloric is already obvious in Carnot's *Reflections*. The basic change in the conception of heat was that it is no longer conceived as heat particles (i.e., an *object*, called caloric), but as energy, which is a *property* of objects (i.e., the energy of an object).
- Is this examples representative for the engineering sciences? Can it be

generalized? Carnot's research question concerning "the limit, set by nature, to the improvement of a technology" is characteristic of the engineering sciences. Nevertheless, there are also other kinds of questions asked in the engineering sciences. Furthermore, Carnot's work is huge. Current scientific articles usually cover a much smaller point, and in this sense it is not representative.