THEORIES AND SPECIFICATIONS

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Abstract
Science employs notions such as *Scientific Theory* and *a Law of Nature* while engineering employs notions such as *Design* and *Specification*. We shall argue that they and their characteristics are central to the distinctive natures of the methodologies of these disciplines.

INTRODUCTION

The discovery of *laws of and theories* is taken to be one of the central goals of the scientific endeavour. Newton’s laws of motion, Einstein’s theories of relativity, the principles of quantum physics, Maxwell’s laws of electromagnetism, Darwin’s theory of evolution and Mendel’s laws of hereditary are some of the most famous. Boyle’s law and the kinetic theory of gases provide a couple of more mundane examples. But whatever their fame and generality such laws and theories form the backbone of contemporary science; their formulation and exploration determines the content and activities of their respective scientific disciplines.

In contrast, engineers deal with artefacts that are *designed, specified* and *constructed* to meet some functional demands (Hyman, 1998; Dym, 1995; Ertas, 1998; Hyman, 1998). For example, an engineer who is employed to design a washing machine already has some notional requirements imposed upon her: it had better wash clothes; to design a toaster is not an option. Here the crucial notions are those of the design process. Requirements have to be elicited, requirement specifications presented and approved, designed created and implemented. So in contrast to science, where laws and theories form the heart of matters, here it is *specifications, designs and implementations*. These dictate the nature and form of the constructed artefact.

In summary, scientists formulate laws and theories and engineers design, specify and build artefacts. We shall suggest, and argue, that it is the properties of these notions that largely determine the very different natures of these activities.
LAWS AND THEORIES

Darwin's Theory of Evolution holds that all life is descended from a common ancestor. It presumes that complex creatures evolve from more simplistic ancestors naturally over time. Random genetic mutations occur within an organism's genetic code and the beneficial mutations are preserved because they aid survival. This is the process known as natural selection. These beneficial mutations are passed on to the next generation. Over time, beneficial mutations accumulate and result in different organisms. Natural selection acts to preserve and accumulate minor advantageous genetic mutations. Natural selection is the preservation of a functional advantage that enables a species to compete better in the wild. This is the theory of evolution in a nutshell. It explains how life has come about and predicts how the world will proceed in the future.

A second example is given by Einstein’s general theory of relativity. This depicts the dimensions of space and time as a two-dimensional surface where massive objects create valleys and dips in the surface. This aspect of relativity explained the phenomena of light bending around the sun, predicted black holes as well as the Cosmic Microwave Background Radiation (CMB). The General Theory of Relativity correctly reproduces all validated predictions of Newton’s theory, but expands on our understanding of some of the key principles. Newtonian physics had previously hypothesised that gravity operated through empty space, but the theory lacked explanatory power as far as how the distance and mass of a given object could be transmitted through space. General relativity irons out this paradox, for it shows that objects continue to move in a straight line in space-time, but we observe the motion as acceleration because of the curved nature of space-time.

The most famous example concerned the solar eclipse of 1919. Erdington’s famous experiment bearing testimony that the light of stars is indeed deflected by the sun as the light passes near the sun on its way to earth. When this phenomenon was first documented, general relativity proved itself accurate to better than a trillionth of a percent precision, thus making it one of the best confirmed principles in all of physics.
Mendelian laws of inheritance are statements about the way certain characteristics are transmitted from one generation to another in an organism. Mendel stated three generalizations about the way characteristics are transmitted from one generation to the next in pea plants. For example, Mendel's second law is called the law of independent assortment. Any plant contains many different kinds of genes. One gene determines flower color, a second gene determines length of stem, and a third gene determines shape of pea pods, and so on. Mendel discovered that where a plant contains genes for color (RR) and for shape of pod (TT), then Mendel's second law says that the two genes will segregate independently.

These theories are meant to be descriptive of nature and the way it functions. They are meant to tell us why things are the way they are. It is intended to be propositional knowledge about the world. It is knowledge that something is the case e.g. light rays are bent when passing near to the sun. They are meant to be explanatory in so far as they explain how life has come about. Finally, they meant to be predicative in that they enable us to predict how the world will behave in the future.

Despite many such astonishing examples of explanatory and predictive abilities, it is quite hard to pin down the central conceptual notions involved namely, explanations, predications and theories are far from philosophically unproblematic notions. Clarifying the nature of explanation is not without its problems nor is what is to count as a relevant experimental predictions i.e., which should be the subject of experiment (Chalmers, 2007). Even, the philosophical nature of laws and theories needs explication.

Fortunately, in this paper we are primarily concerned with the bold picture that science presents. In particular, we shall only assume that scientific theories may have to be given up in the light of experimentation i.e., if the predictions turn out to be false, the theory may have to be revised. Whatever position one takes on the induction/falsification/confirmation issues in science, this is a minimal requirement.

Theory construction is defisable.
The big picture is clear. Theories purport to provide knowledge about the world. But while its generality provides explanatory and predictive power, it pays the price of being defensible knowledge. Theory construction cycles through alternate stages of theory articulation and empirical verification.

**DESIGNS AND SPECIFICATIONS**

In contrast, engineers deal with constructed artefacts that are designed and built to meet some design specification. Two possible engineering design problems are the following.

1. An incubator to be used in under-equipped medical clinics in developing countries. The incubator will maintain samples at temperatures (35° - 37° C). It will have a capacity of at least 10 10-ml test-tubes or 3 100-mm Petri dishes. The cost will be less than £100.
2. A computer store is to have named locations that hold numerical values. There has to be some means of obtaining the content of any given named location and a means of changing its contents.

These provide *specifications* of two desired artefacts. They list some of the attributes that are demanded of the latter. While they leave much unsaid, they already demand a good deal. In particular, an engineer who delivered an artefact that satisfied the requirements of 1, when asked for those of 2, would be fired. So unlike scientific theories that have a descriptive function, specifications are *normative* in nature.

Nevertheless, they leave much unsaid. Part of the task of this first specification or problem statement is to get things as precise as possible. The above leave several questions unanswered. For example, for how long is the incubator to maintain the required temperatures. And in the second, when the location’s contents are changed, and the contents of another location are abstracted, its contents should not be changed. All this is left implicit. Part of the task of the specification is to get things as precise as possible. Where feasible, mathematical descriptions can help. For example, in the case of the second we might provide a mathematical description of the store the two operations (call them *Update* and
According to our informal remarks these should be governed by the following conditions.

\[
\text{Lookup}(\text{Update}(s, x, v), x) = v
\]

\[
\text{Lookup}(\text{Update}(s, x, v), y) = \text{Lookup}(s, y) \quad \text{where } x \neq y
\]

This is an abstract mathematical description of the properties or requirements of the proposed physical device.

Once the design problem has been as specified as precisely and completely as seems possible, the next phase of the design process involves the invention of possible solutions i.e., designs for the physical devices that meet these requirements. The design team usually generate a family of possible solutions. Often existing solutions are taken as the starting point and improved upon. In this case existing designs for computer stores might be the starting point. There will be design requirements not specified in the abstract specification, such as what materials to use, whether it be a mechanical device or a digital one with silicon components etc. All of these considerations would need to be made explicit in any realistic design solution. Of course, solutions evolve and the whole process of constructing one is most often an iterative one.

But at some stage a single design solution needs to be selected. Economic, safety, correctness to requirements and security considerations provide the criteria for selecting the more promising alternatives that eventually results in a single design specification.

At any step of the design process the solution chosen may prove unworkable and may require collecting more information and generating different solutions. However, at some point in the design process the design specification must be fixed and become the basis for the construction of the physical device. This is made clear by Kohn (Kohn, 2003).

**HEURISTIC:** At some point in the project, freeze the design

This rule of thumb recognizes that a point is often reached in design where the character of a project, and hence the appropriate allocation of resources, changes from seeking alternative solutions to perfecting a chosen solution. As might be expected, this point is located heuristically by a trade-off between the relative risk and benefit of seeking yet another alternative. After this point is reached, a major design change runs an
unacceptable risk of introducing a fatal flaw because insufficient resources remain to evaluate all of its ramifications. Once a design has been frozen (as a good rule of thumb, about 75 percent of the way into the project), the members of the design team take the general attitude, let’s go with it.

And this point the normativity of the design solution is made explicit. So that not only do we have the original specification taking on normative force, but the actual design of the artefact itself eventually must take on this persona.

Like scientific theories, specifications and designs may have consequences, and these can act as predictions about the properties of the constructed device, and become the focus of its testing. However, in other respects to two sets of notions are different. In contrast to laws and theories, designs and specifications are not intended to be explanatory. Instead, they are intended to provide a normative guide to the construction of the artefact. They provide a notion of malfunction and a notion of correctness. If we build a computer store instead of an incubator when asked for the latter, then we have not correctly implemented the specification. More locally, the physical device may not measure up to its design solution. In such cases, we say that the device has malfunctioned, and does not reflect the designer's intentions. If it fails, the device needs to be rebuilt. Specifications and designs are not descriptive of the world; they are not knowledge that something is the case. Rather they provide knowledge of how to construct something. They are knowledge how rather than knowledge that.

THE SCIENTIFIC STANCE

Another prima facie difference between science and engineering resides in the nature of artefacts. By and large, engineering deals with constructed artefacts and science with natural occurring phenomena.

But this difference does not really get to the heart of matters. It does not reflect the different methodologies of the two activities. In particular, scientific theorising need not be about natural phenomena.

Indeed, one may take what might be broadly described as a scientific approach or stance with respect to engineered artefacts. More explicitly,
such artefacts may be explored scientifically. Here the physical device is the thing that is given to us. It might be known to be a constructed object. But we may not understand how it works. Consequently, we might well take a naturalistic stance towards it and treat it as a natural artefact. The scientific task is to figure out what it does and how it works.

For example, imagine a simple physical device that is a large white box with small individual black windows. The windows are named with letters of the alphabet. There is small attached keyboard with letters on the upper case keys and numbers or blanks on the lower case keys.

We press the keys and carry out some simple experiments and we notice that pressing the upper case letter above a window displays a number behind the window. Further exploration reveals that pressing an upper case letter immediately followed by a number on the lower case keys, changes the content of the window named by the letter. Consequently, we postulate the idea that the whole device it is a simple store with Update and Contents operations. In other words, on finding this device, we attempt to construct some kind of theory about the machine i.e., we postulate an abstract machine as a theory of the physical one. We might even formulate axioms $1$, $2$ as the theory of the device.

On this perspective, these operations are determined by what the physical machine actually does. For instance, if, when given $y$ and $6$, the physical machine generates the state

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<th>$X$</th>
<th>$y$</th>
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<tr>
<td>5</td>
<td>7</td>
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We might postulate not $1$, $2$ but that the following equation that governs its behaviour.

$$\text{Lookup}(\text{Update}(s, x, v), x) = v + 1$$

This is the scientific approach to artificial artefacts. Methodologically, this is science not engineering. The simple conditions $1$, $2$ no longer
constitute a specification of a device, but act as the basis of a scientific theory about it.

**THE ENGINEERING STANCE**

On the other hand, naturally occurring artefacts can be reverse engineered. In which case, we will use the relevant scientific knowledge to specify and design the artificial one. While this is so for most design projects, here we are specifically trying to reverse engineer a naturalistic artefact. We may, for example, wish to reproduce a dog's nose. We shall use any scientific theories about noses and sniffing in order to inform our specification and the design of the artificial nose. The specification will have to abstract away from the physical nose, and maybe compromise on its sniffing power. A dog's nose has something like twenty times as many primary receptor cells as the human nose, and different regions of the mucous lining within the nose have different chemical properties. Unfortunately, for our engineering task, canine noses are still a bit of a mystery. And so we may have to settle for a child's nose: its power may be restricted to its ability to sense breast milk.

Indeed, reverse engineering may even involve an initial scientific phase where the natural version of the desired artefact is treated scientifically. For example, we might build scientific theories of dog's noses in order to eventually engineer the artificial one.

**NORMATIVITY AND DEFESABILITY**

These simple observations tease out some of the differences between what we might call the scientific versus the engineering perspectives.
For one thing the major differences are not located the artefacts or phenomena. Our intentional stance determines how we treat them. Engineers and scientists treat objects in different ways, whether they are natural or not.

The scientist will approach any object with the intention of understanding it via the construction of a theory about it. Theories are postulated and tested and amended until some kind of stability occurs. But there is never an end to this process. Such theories are always up for revision; they are always defensible. The resulting knowledge obtained from theories is propositional knowledge about the world and the way it functions.

In contrast engineers design artefacts. And design specifications act as normative guides to the construction of the actual artefacts. The eventual specification and design is not taken to be a theory of anything. And this is true even if there was some initial reverse engineering. The specification is not meant to be a theory of an existing artefact but a design for new one. And within the design is encoded knowledge about how to build it. It is knowledge how rather than knowledge that.

Undoubtedly, these characterizations oversimplify both engineering and science, and indeed, their relationship. For one thing, scientists do not change their theories as easily as this simplistic characterization suggests. So-called normal science, where a theory dominates, can last some considerable time. The move from Newtonian to Einstein's physics is often cited as an example. Indeed, major changes of theory, the big paradigm shifts, happen quite infrequently, and during the periods of normal science, theories play a more normative role.

In a parallel way, the engineer does not hold onto the specification no matter what. Its normative status may be given up in the light of continual practical failures to build a device that satisfies it. It may just turn out to be physically infeasible. However, this is the last, not the first, resort.
Bibliography


