Einstein got it Wrong (for once) – Some Consequences for Problem-Based Learning

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ABSTRACT

Differences between theory and practice are often discussed, usually leading to misinterpretations of both, and of their relationships. It is assumed that there is a conflict situation.

A misinterpretation of theory occurs mainly in the opinions of theoreticians, who claim that a phenomenon "is governed by theory." On the contrary, theory tries to provide a scientific description of a phenomenon, and underpin it by a set of logically interpretable models. Misinterpretation occurs also with respect to practice. Every practice is concerned with the object – real or process, and the method – of use of the object, and of designing the object.

The relationships among theory, object and method are discussed, and it is shown that these three form a coordinated triad. A further comparison is made between the theory-object-method triad, Kolb's model of learning styles, and advice given by Confucius. This demonstrates that problem-based learning is probably a good model for educational presentations, but must be supplemented by formal explanations of the theory, and formal demonstration and practice of the method for that particular topic of learning. This is particularly true for education in designing.

1. INTRODUCTION

A recently received e-mail message contained a quote attributed to Albert Einstein:
"In theory, there is no difference between theory and practice; in practice there is."
This quote from Einstein is wrong on several counts, and therefore needs a more extensive discussion. It leads to misinterpretations of both theory and practice, and of the relationships between them. It assumes that there is a conflict situation, a dichotomy. The falseness of the impression of dichotomy can be shown by several other quotations from eminent people:

"Theory and Practice are not antagonistic, as is so often tacitly assumed. Theory is not necessarily unpractical, nor Practice unscientific, although both of these things may occur ... It is not a matter of merely setting forth in a new form and order that which is already known ... On the contrary, if the new theory is to lay claim to general interest, it must be capable of producing something new; it must make problems solvable which before could not be solved in a systematic way." [1]

"Before examining the contribution of theory, I want to say a few words about the unsound and unworkable distinction often made between 'theorists' and 'practitioners.' The musings of educational theorists are often contrasted with the practicalities of teaching, theory and practice being viewed as existing on either side of a great, and unbridgeable, divide. I believe this theory-practice dichotomy is a nonsense. Making this distinction is epistemologically and practically untenable. Like it or not, we are all theorists and all practitioners. Our practice is informed by our implicit and informal theories about the processes and relationships of teaching. Our theories are grounded in the epistemological and practical tangles and contradictions we seek to explain and resolve. The educational theory that appears in books and journals may be a more codified, abstracted form of thinking about universal processes, but it is not different in kind from the understandings embedded in our own local decisions and actions. As Usher [2]suggests, formal theory serves as 'a kind of resource and sounding board for the development and refinement of informal theory – a way of bringing critical analysis to bear on the latter.[3]

"We cannot decide what was superstition and what scientific observation, so long as we look at results, theories, theses, beliefs, or any content. Whether a particular opinion is scientific or superstitious depends on the method by which this insight was gained. Did it integrate the available experience? Was there any means of checking it through observation or experiment? Did it satisfy the laws of logic and, in particular, did it presuppose a reasonable relationship between cause and effect? Finally, did it assume a self-contained universe?" [4]

Nevertheless, a closer investigation is needed. Especially, an implication exists that there is either "no difference" between theory and practice, or that the difference is necessarily absolute. We must explore not only the admitted differences, but also the commonalities.

2. NATURE OF THEORY

A misinterpretation of theory occurs mainly in the opinions of those theoreticians who claim that a phenomenon "is governed by theory." On the contrary, theory is governed by the phenomenon. Theory tries to provide a formal and consistent scientific description and explanation of an existing phenomenon, and if possible to underpin the phenomenon by a set of logically interpretable models. The phenomenon exists irrespective of whether the theory exists.

Scientific activity to generate theories has been described by the myth of "scientific method," which seems to prescribe a sequence of (a) observing – undirected, at random, (b) experimenting, (c) forming hypotheses, (d) theorizing. In fact, most scientific experiments are performed after hypothesizing, and are conducted mainly with the view of confirming the hypothesis. Peter Medawar said: Scientists don't ask questions very loudly until they can see the beginnings of an answer. Any observations that run counter to the hypothesis are initially discounted, ignored, and their significance down-played or denied. Conducting scientific investigations requires some flair, ability, intuition, etc. to produce valuable additions to knowledge (these are usually classed as artistic traits). Most routine additions stay within a disciplinary matrix [5,6]. Only when the additions can no longer be made to fit can scientific revolutions take place. Scientists are creative when they investigate a variety of hypotheses, just beyond the current limits of scientific acceptance, not too far or it becomes "unscientific" [7].

Theory is the result from much thought about a phenomenon, conjecturing how it can be explained – hypothesizing. This is subsequently coupled with a directed observation (if possible with measurement) of the phenomenon, whilst attempting to exclude those effects that may disturb or obscure the observation. These two components, conjecture and thought, and observation and measurement, are the bases of a truly "scientific method."

Gregory [8] states that the maturity of science about a body of knowledge (e.g. knowledge about designing) "is characterized by a gradation of behaviour which may be expected, and which causes that knowledge to be reckoned as scientific." Clearly, this relates to the epistemology of the knowledge, the theory of the methods or grounds of knowledge, the ways of knowing [9]. This behaviour and the state of organization of the body of knowledge may range through:
(1) description of phenomena (natural history phase);
(2) categorization in terms of apparently significant concepts;
(3) ordered categorization whose pattern may be deemed a model (the evolutionary taxonomy or periodic table phase);
(4) isolation and test of phenomena, with implied reproducibility by independent observers;
(5) quantification (classical physics phase).
Even the first of these is commonly acknowledged as "science" when applied to a traditional area of study (e.g. biology). Many areas of science cannot reach the final "quantification" stage in which mathematical relationships are formulated. Engineering design, the process of designing, is obviously such an area, but this observation must be qualified by the connections to other knowledge. Designing as an area of scientific investigation, codification of knowledge and theorizing can, in parts, not even reach stage 4, because the human element is not strictly reproducible – humans are idiosyncratic, and have their own decision powers. Some of the knowledge we use and interpret for engineering design exists at the highest scientific levels – it may be useful for analysis of proposed solutions, but the choices and values are human.3.

NATURE OF PRACTICE

A more important misinterpretation occurs with respect to practice. Every practice is concerned with two aspects:
a) the object of concern, a real or a process object, and
b) the method – of use of object, and/or of designing the object.
Some people claim that they do not use a method. Such a claim is obviously false if the person performs repeatably in a task: repeatability implies a set procedure, a method. Deliberately applied, the claim of "not using a method" is tautological, the person uses the method of avoiding all other known methods. If the claim were absolutely true, it would lead to purely random action, without reflection [10] or learning.

Use of a method usually involves applying some heuristics [11] to help in solving the problem. This discussion should be coupled with the idea of "putting theory into practice" – which should rather be stated as "putting theory behind practice," or "underpinning practice with theory." A similar falsehood consists of "technology transfer," implying transfer only from research into industry, i.e. from theory into practice. Transfer always goes both ways, even though some spectacular "high-tech" things appear to come from pure theory. Related ideas show that feelings and emotions are always present, more than 90 % of our actions are governed by feeling and emotion, rather than by reason. Emotions are built into our mental and physical system, they act even in the highest realms of science and research [12].

In order to use or formulate a method related to a particular object, the user (and/or formulator) must have some idea about how the object will behave under this use. An informal or formal theory must exist, at least in the mind of the user, and conjecture and case-based reasoning will be applied. The relationships among theory, object and method therefore need to be discussed, they form a coordinated triad.

4. THEORY, METHOD, OBJECT

As Klaus [13] formulated in cybernetics (see also [14]), close relationships exist between the object under consideration (its nature as a product or process), the basic theory, and method, as figure 5– 4 in [15] shows. The theory should describe and provide a foundation for the behaviour of the (natural or artificial, real or process) object, i.e. it should answer the questions of "why," "when," "where," "how" – its natural behaviour – with adequate and sufficient precision. The theory should also support the utilized methods, i.e. answer the questions of "how" – procedure, "to what" – object, both for using and/or operating the object, and for designing the object. The method should also be sufficiently well adapted to the object, its "what" – existence, and "for what" – anticipated and actual purpose. These three phenomena of theory, method and object are of equivalent status to each other. A mutual interplay between object (and phenomenon), theory and method, one refined and examined on the other, characterizes the normal human social and scientific development and progress. Quoting from Klaus:
' Both method and theory emerge from the phenomenon of the object.'
If the theory of an object-region is mature, then the method is founded in the theory. The theory declares what is in reality the case, the method describes, on the basis of the declared facts, how the scientific and practical activities and behaviours of the humans should take place.

Where no comprehensive theory is available, methods to deal with objects can be proposed, even where the structure of the objects or their behaviour is not completely known (this is the cybernetic and newer interpretation). The method can conceivably have the character of an input-output-relationship ('black-box' principle, first formulated by Ashby in 1956). We know that corresponding results will be generated when we act on a system in a certain fashion. The theory will then, once it is developed – which often happens after a lengthy delay – give an explanation of why this is so (to some extent an interpretation of the input-output relationship).

The relationships among objects, methods and theories are significant for the situation of heuristic methods. For many currently interesting problem groups we lack an appropriate theory which can explain the method for its treatment and solution. In such problem situations, the method (frequently an heuristic method) must first serve to open up the problem field and disclose the structure of the problem. This kind of problem situation is increasingly found in recent research efforts, and therefore the interest in heuristic methods is rising.

Methods are generally prescriptions for action, and help to explore, reformulate, search the solution space, evaluate and choose among the available choices, guide towards a resolution of the problem, etc. Methods can be collected into sequences with logical connectivity, then called methodologies. Methods can be (somewhat arbitrarily) classified into strategy and tactics. A strategy provides a broad outline of the approach to a problem, tactics provide detail operational advice. Problem solving methods are usually regarded as tactical. "Practice" is thus seen to be a fuzzy conglomerate of theory, method and object.

5. TYPES OF KNOWLEDGE

As a major part of the structure of Design Science [15], the codified knowledge about designing, we have defined a four-sector model of knowledge (see figure 1). The horizontal axis of the model represent the contrast between object and process knowledge. The vertical axis contrasts theory (descriptive) knowledge with practice (prescriptive, heuristic and applications) knowledge.

In a methodological category of knowledge, we distinguish descriptive (theoretical), prescriptive

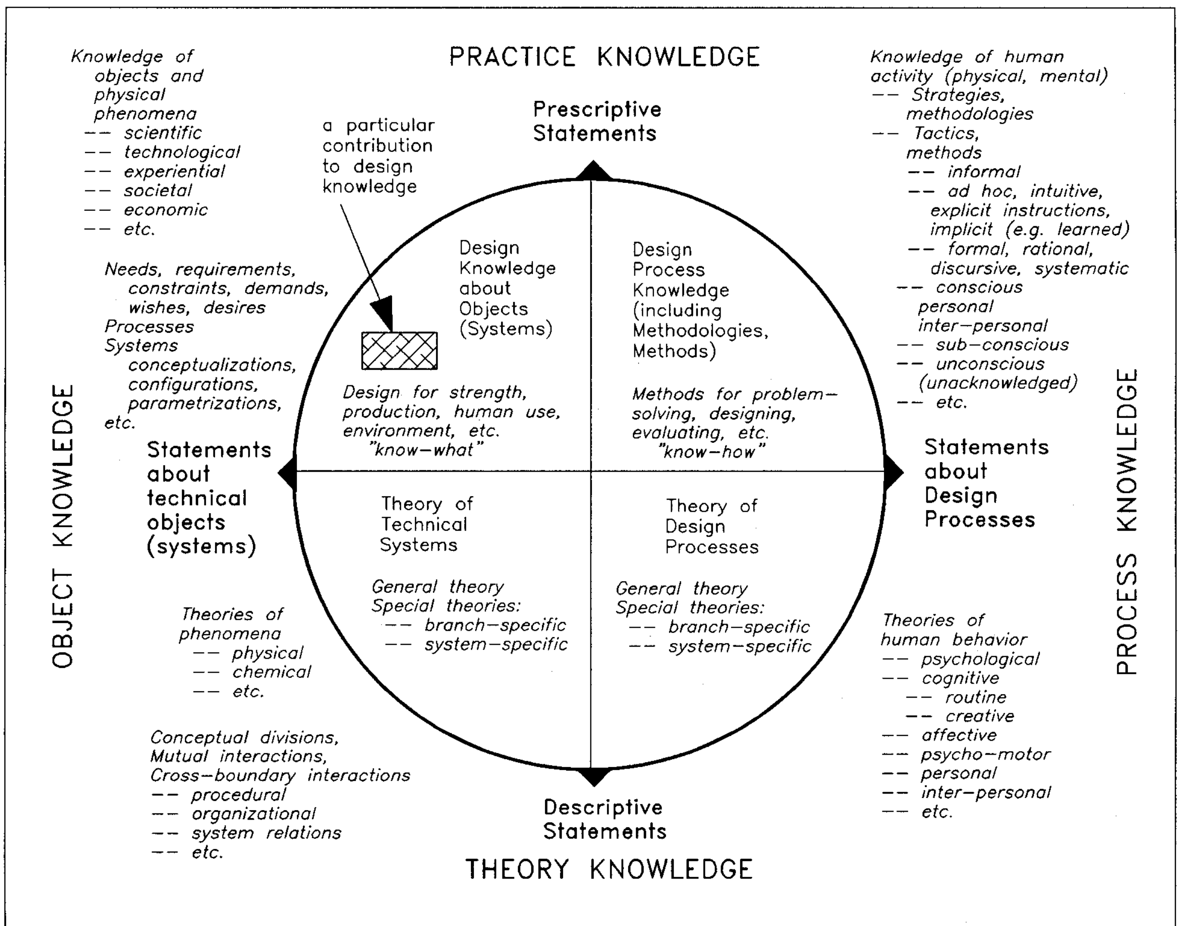

Figure 1 Categories of Engineering Design Knowledge [17]

(advisory, including heuristic) and normative (compulsory, established by a standard or law, regulative) statements. We usually combine the normative statements into the prescriptive group. Note that the usual English-language usage of the word "descriptive" concerns narrative, anecdotal or essay descriptions with little theoretical basis. Our usage of "descriptive" in Design Science [15] refers to the declarative and theoretical concepts, which are derived from and supported by the narrative descriptions and empirical results. The respective structures of knowledge in the north (prescriptive) and south (descriptive) quadrants in each half (east – design processes, west – technical systems) are identical, the contents differ.

With respect to object knowledge (the left side of the model), there is a strong link between several kinds of knowledge:
(a) knowledge that can be used directly for designing (usually classified as "design for X"). This includes knowledge about all properties of a product, and its life cycle, especially the manufacturing and usage phases;
(b) knowledge about various classification methods for available knowledge, especially for information research, storage (archiving) and retrieval;
(c) various object theories to describe and explain phenomena, including the engineering sciences, the "pure" sciences, the humanities, social, political and other theories; and
(d) the generalized theory that fundamentally describes the nature, structure and performance of an object (product) [16], especially the features and properties that all products should have.
The object knowledge for a particular product is a specialized version of these kinds of knowledge and information.

Equally, there is a strong relationship among elements of process knowledge:
(a) method knowledge that can be used directly for designing, including problem-solving, transforming various kinds of models of products, abstracting and concretizing, etc. [17];
(b) the generalized theory of design processes.
Both kinds of design process knowledge must be adapted for the particular design problem.

It should be obvious that a good theory of designing and its application to products (see for example [15,16,17,19,20]) should be, and is, closely coordinated with the theories and methods related to object knowledge. All four sectors interact. This division of knowledge (figure 1) should provide a suitable model for teaching and learning. It can help to set guiding principles for structuring the contents and exercises for engineering courses.

It should also be obvious that methods are prescriptive and advisory. Methods can also be used for other tasks related to designing and its industrial context [15], e.g. communicating, negotiating, feeding information into design, generating ideas, problem solving, evaluating (in part helped by analysis), deciding, representing, modelling, auditing, verifying, checking, etc. Several methods are quality-related, others deal with the possibility of concurrency of work on different modelling levels or design stages, etc.

Even though each method (and methodology) has its prescription, no human can carry these out in a linear manner. Each method contains several problem solving cycles, and must be performed using iteration (going back to complete and revise previous results) and recursion (breaking a larger problem into smaller ones, solving, reintegrating and synthesizing into the larger solution), and adapted to the problem and the solver in context.

Designing involves some flair, ability, intuition, creativity [20], spontaneity, etc. (and consequently some mystery), but also judgment, reflection [10], conjecture and case-based reasoning, feel, and experience of individual designers. It is necessarily heuristic [11], iterative, recursive, opportunistic, flexible, and idiosyncratic. Teamwork among designers and other participants plays a large role in the design process. Some of these factors may even be computer-assisted. All these are more or less essential to designing, but as individual statements none of them captures the essence of designing, they are necessary, but not sufficient conditions. They seem to indicate that designing is purely a very personal and human matter.

Nevertheless, designing is not isolated, it concerns an activity, performed within an organization and under specific circumstances, and it concerns an object – a product. Some coherent and comprehensive systematic and methodical procedures are available from and within Design Science [15], and are useful, if applied appropriately and flexibly. Other attempts to provide methods exist, they mainly consist of prescribing parts of the process. Examples are found in [21] which deals with the theory and mathematical methods of decision-making, and [22] which delivers an informal collection of methods. Methods include heuristic and "industry best practice" methods, which are usually reported without an adequate theory of either the design process or the generalized object being designed. Most of these can be related to Design Science [15] and integrated product development [23].

6. CONSEQUENCES FOR PROBLEM-BASED LEARNING

A further comparison between the theory-object-method triad, Kolb's model of learning styles, and advice given by Confucius demonstrates that problem-based learning is probably a good model for educational presentations. But it must be supplemented by formal explanations of the theory, and demonstration and practice of the method for that particular topic (object) of learning. There is consequently also a need for theory, method and content (object) of the teaching/learning process itself. Such a theory, in the English-language regions, is fragmentary and incomplete. A more complete and coherent system of theory and method has been proposed in the German literature, under the terminology of pedagogics and didactic, the theory and strategic and tactical methods of education. In English, the words "pedagogy" and "didactic" have more pejorative meanings.

The problem-solving modes recognized by Kolb [24] as preferred styles of thinking are:
1) Concrete experience (CE) – tendency to experience something "concretely" and to analyse that experience, which is needed for 'clarifying the task' in the problem-solving cycle;
2) Reflective observation (RO) – tendency to reflect on an experience, observe and describe, needed in a 'search for solutions' in problem solving;
3) Abstract conceptualization (AC) – tendency to conceptualize observations by means of abstract models, hypotheses and concepts, essential for 'evaluating' possible solutions in problem-solving;
4) Active experimentation (AE) – tendency to actively experiment to test and extend models,

needed for 'evaluating' solutions and 'decision-making' in problem-solving.
The model suggests (and shows by means of a psychological test instrument) that people are not equally good at these separate tasks. Kolb classified types of people from these activities according to their best learning styles into:
a) accommodators (preferred sector delimited by axes AE and CE)
b) divergers (sector CE – RO)
c) assimilators (sector RO – AC)
d) convergers (sector AC – AE).

This cycle of four activities can be started anywhere in the cycle, but for effective learning to take place Kolb indicates that these steps should be followed, preferably sequentially, and all stages should be completed. Both object and process knowledge must be presented as completely as possible and with good theoretical explanations. It must then be understood, practised and built into the existing mental frameworks by students, in incremental stages such that all four thinking styles are activated. An implication is that students also need to learn those processes which are not their best ones, and preferably under good guidance. Best teaching (leading to learning), especially for engineering design, does not consist of dumping students in at the deep end of design projects (e.g. capstone courses, and competitions) and letting them sink or swim.

The theory, methods, examples and practice for any particular topic should be introduced in suitable stages, coordinated with the progressive increase in difficulty and complexity of the problems – it is definitely not advisable to present all the theory (or method, or practice) in one chunk. A useful guideline, attributed to Confucius, says:
"Tell me and I will forget
Show me and I will remember
Involve me and I will understand
Take one step back and I will act."
In the usual interpretation, the first two of this set of items are often used to deny the effectiveness of lectures and demonstrations, and to advocate that only project-based education leads to learning. The last of these items is usually omitted – and, according to the same logic, would lead to rejection of project-based learning. These four statements are not alternatives, they are mutually additive. Inducing learning requires a combination of explanation (telling), demonstration (showing), coaching (involving), and gradual release from supervision (stepping back). Consequently, I would add:
"Do all four and I will become competent."

The goals for teaching should be elaborated in reasonable detail to guide this engineering design teaching. An example is given in [18,20] of goals to achieve creativity, which includes presenting the systematic methods of designing. This comprehensive consideration of design process, product, theory, method and the human should take place during the whole of engineering education, throughout the (3 or 4) years of the course, not just in specific design courses, especially not just in capstone courses. Such factors can lead to competency, as defined in [25], with recognizable sub-groupings of competency in heuristic, branch-related, methods-related, systems-related and social aspects.

7. CLOSURE

The main differences between theory and practice lie in the procedures to be followed. A theory should be as complete and comprehensive as possible. Practice must take into account the human capabilities and traits, it must allow a method to be used flexibly, iteratively, recursively, etc. Nevertheless, practice (as method applied to an object) and theory should be closely related. This applies for general scientific investigation, for engineering design, and for education.

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