Learning through artifacts in engineering education: Some perspectives from the philosophy of technology and engineering science

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Abstract
Human experience of our world is shaped and transformed by physical and symbolic tools (mediating tools). The concept of mediation could be represented by: Human ⇔ Mediating tools ⇔ World. Questions about the role of technology (artifacts) in everyday human experience include: How do technological artifacts affect the existence of humans and their relationship with the world? How do artifacts create and transform human knowledge? How is human knowledge incorporated into artifacts? What are the actions of artifacts? Tools (i.e. conceptual and physical artifacts) play an important role in human thinking and learning. However the role of technology is frequently missing, or insufficiently evaluated, in educational analysis. Herein, I reflect on Dewey's notion of "education as engineering". Considering the importance of the use of tools in education, I claim that education could, in one sense, be seen as an engineering science. Engineers are trained in design, especially in artifact design, and in understanding and improving complex systems. They should be trained to understand that humans are also part of the systems that they work with. Thus, approaches and knowledge from the perspective of engineering science and the philosophy of technology can contribute to the understanding and development of engineering education.

Keywords: Engineering education research, philosophy of technology, educational design, mediation.

1. INTRODUCTION

In the summer of 1978 I conducted the empirical work for my Master's thesis in engineering fluid mechanics at a pulp and paper mill. In my work I used modeling and computer simulations (for which I had to write all the code myself) to design a system for wastewater recycling. Using a computer for parts of my work was "admired" by the older engineers. They believed that the simulations must be "true" because they were "produced by a computer". However, in my mind, it was risky to put to much faith in the results of a model and, therefore, I included a section in my Master's thesis on the importance of adopting a critical and reflective stance towards models and modeling.

Engineering education research is currently emerging as a specialized branch of research worldwide. The working group for *Engineering Education Research* of SEFI was inaugurated one year ago at SEFI2008 in Aalborg. Engineering education research has also recently been established as a program for doctoral study at many different institutions around the world; for example, at my own university the first doctoral thesis was defended in 2006 by Margarita Holmberg (née González Sampayo) [1]. It should be noted that Dr Holmberg obtained her first degree in electronics and telecommunications engineering. Her Ph D was awarded by the school of engineering and is an engineering doctorate.

Conducting research in engineering education is not the same as doing research in engineering. One could focus, as Maura Borrego [2] did, for example, on the "conceptual difficulties experienced by … engineers learning educational research". However, as mentioned above, I included a critical discussion about modelling in my Master's thesis in engineering. I have now been involved in engineering education research for more than a decade. An important topic within my educational research is related to the role of models and modeling in engineering education. Thus, what I currently do as an "educational researcher" is very much related to what I did as an "engineer" more than thirty years ago. In 1922, almost ninety years ago, John Dewey wrote his wonderful essay "Education as engineering" [3]. Most learning environments use some kind of technology (artifacts[1] in the form of physical and symbolic tools) and, as succinctly expressed by Carl Mitcham [4], we "think through technology". Considering the importance the use of tools has in education, I maintain that education could, in one sense, be seen as an engineering science. Engineers are trained in artifact design and in understanding and improving systems. They should be trained to understand that humans are part of these systems. So called 'design-based research' or 'design experiments' have begun to appear as a research approach within education [5, 6] and it should be noted that in French the term coined for this approach is "ingéniere didactique" ("didactic engineering") [7]. In this methodology, engineering metaphors for design studies have, according to Anthony Kelly [8], proved useful.

As a researcher and as an educator I have been involved in studying and developing technology-rich learning environments in engineering education. My own schooling included studies in engineering and in philosophy and both provide essential foundations for my research in education. Below I describe areas of the philosophy of technology that are also a philosophy of education and a philosophy of mind.

Thus, in this essay, I focus not on "conceptual difficulties" – instead I focus on what the science of engineering and what studies of technology can bring *to* research in, and design of, education – especially engineering education. I focus, in particular, on the role of artifacts (physical and symbolic tools) in human cognition. In this domain engineering knowledge has a special potential to contribute to theory development as well as improving the practice of education.

2. EDUCATION AS ENGINEERING SCIENCE

In his essay "The Structure of Thinking in Technology" Henryk Skolimowski [9] put forward the suggestion that "it is erroneous to consider technology as being an applied science" (p. 372) and he continues with a comparison, noting that "in science we *investigate* the reality that is given; in technology we *create* a reality according to our designs" (p. 374, italics in the original). He summarizes this as "science concerns itself with what *is*, technology with what *is to be*" (p. 375, italics in the original).

A "technological object" is, according to Skolimowski, "every artifact produced by man to serve a function" (p. 375). Therefore, I maintain that the design of a learning environment could, indeed, be seen as the design of a "technological object", i.e. an artifact. A similar reasoning can be found in Anthony Kelly's [8] discussion of 'design research in education': "[A] design is not [a] design without some form of designated artifact" (p. 116). He continues "in my opinion, design studies should produce an artifact that outlasts the study and can be adopted, adapted and used by others … The design of such artifacts usually involves *engineering* a broader 'learning environment'" (pp. 116-117, my italics). Hence, as proposed by Dewey, education can be regarded as "engineering", indeed, he called for the development of an "art of educational engineering" [3].

The differences and tensions between "science" and "technology" discussed above by Skolomowski are also present within educational research. Some researchers investigate education and student learning as a "reality that is given" and see teaching praxis or the design of teaching and learning environments as only a matter of applying educational theory. However, as any engineer knows, Maxwells' equations are not sufficient for the construction of an amplifier circuit nor are Newton's laws sufficient for building a bridge. Similarly in "The sources of a science of education" Dewey [10] states that "no conclusion of scientific research can be converted into an immediate rule of educational art" (p. 9). For Dewey [3], therefore, engineering is not simply about applying knowledge from science to practice. According to Dewey knowledge is gained, in engineering, by *doing* things differently and in this way engineering knowledge is practical or in his words "there was … no definite art or science of modern bridge-building until *after* bridges of the new sort had been constructed" (p. 324). He continues by pointing out that the theory developed as a result of a new achievement couldn't precede the achievement.

However, Dewey [3] also pointed out that it is not fruitful to take the approach of "blindly trying one's luck or messing around in the hope that something nice will be the result" (p. 326). Rather, he points out, "pioneers in the educational field need an extensive and severe intellectual equipment" (p. 326), they need "imagination, courage and the desire to experiment and to learn from its results" (p. 325) but that, nevertheless, there exists a "certain amount of dependable knowledge" that can be relied upon and can be used to proceed with any endeavor. The problem is how to use this knowledge in "new social conditions" and that imagination should not be limited "to what was already familiar" (p. 325). He stresses engineering as a human enterprise by pointing out that "the essential need was thus human rather than scientific" (p. 325). Education is a human enterprise and is a domain well worth the attention of engineers and appropriate for the application of engineering knowledge.

[1] The alternative spelling "artefact" is used in some literature.

Dewey's stance in "Education as engineering" [3] adheres very well with an emergent approach called "design-based research" or "design experiments". According to The Design-Based Research Collective [6] design-based research "must account for how designs function in *authentic settings*. It must not only document success or failure but also *focus on interactions* that refine our understanding of the learning issues involved." Cobb *et al.* [11] described this shift as follows: "Prototypically, design experiments entail both 'engineering' particular forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them. This designed context is subject to test and revision, and the successive iterations that result play a role similar to that of systematic variation in experiment".

The statement by Lo *et al.* [12] five years ago that, *inter alia*, the main "benefits of design experiments [in education] are that [they] will … contribute to theory development, and improve practice at the same time" sounds very similar to the position taken by Dewey that the development of practice and theory is closely and synergetically related. In the "design-based research" or "design experiments" approach, insights from design and engineering are employed to address the complexity of educational activities and the need, as known from engineering, for theory as well as tinkering.

While revising this paper I came across a recent special issue of the *Journal of Curriculum Studies* [13-17] thoroughly discussing Dewey's paper "Education as engineering" [3] and the paper is reprinted in the special issue [14]. The interpretations of Dewey's views on education put forward by the authors of the papers in this special issue are very similar to mine. In particular, I would like to present an excerpt from Hopmann [16], citing a Norwegian engineer:

> "When I first came across Dewey's wonderful piece 'Education as engineering' … it proved to be very helpful in my day-by-day work at the Norwegian University of Science and Technology (NTNU) at Trondheim. Most of my partners in projects and university affairs came from engineering; indeed, one of my closest colleagues was a bridge-builder in the original sense of the word, having designed and built bridges across Norway and elsewhere.
>
> He often complained about the misconceptions of engineering that many of my social science colleagues seemed to have. 'Of course you've got to do the math right', he said:
>
> 'but when it finally comes to building a bridge, you've got to understand the uniqueness of the site you are approaching. This requires a deep understanding of what this bridge will be, how it will fit into the landscape and to the needs of its customers, an understanding, which we can't teach at universities, which only can be acquired by doing bridges.'
>
> For him the argument in Dewey's short essay about the nature of knowledge in engineering and about the short-comings of an educational theory not firmly rooted in preceding practical improvement seemed to be a perfect fit ..."

Engineering science have learned to handle the general (in the case of bridge building: engineering mathematics, solid mechanics, materials science, geology …) and the particular (the local situation of this particular bridge). This is reflected in Dewey's understanding of engineering as an "art" and a "science". Furthermore Carl Mitcham [4, p. 203] reminds us that "Technology is not so much the *application* of knowledge as a *form* of knowledge". In line with this, the quotation above about the Norwegian bridge builder very much captures the essence of "technology as a form of knowledge". This also relates closely to the old Greek distinction between 'episteme' and 'techne' [18]. The concept of 'techne' has, until recently, been neglected in philosophy but is of great importance for engineering. This concept takes into account the fact that engineering needs theory as well as tinkering and that engineering knowledge is related to praxis, i.e. in order to make things work.

Furthermore, the discussion above fits very well with what I learned during my engineering education. The things I learned include:

- Humans are part of any technical system.
- Most systems are complex.
- Scientific theories do not provide sufficient knowledge for successful design, but they can be used as a starting point.
- Designing is always a contextualized practice and must address the possibilities and restrictions in the actual context.
- Designing should take account of diverse and sometimes conflicting aims.
- Designing is not neutral, but is a value-laden practice.
- There is no "best" design and many different solutions are possible.
- Adherence to details is critical for successful design.

Therefore, I maintain that engineers have many competencies that could contribute to the development of the "art of educational engineering" especially in engineering education. Important insights from engineering that would be of great value if they could be transferred to education are: knowledge about design; knowledge about artifacts in design and cognition; and, especially, the development of knowledge that takes into account the general as well as the particular and contingent. As a consequence, research in engineering education should be seen as a research field well worth the attention of engineers and should be regarded as a branch of engineering research.

The use of artifacts (symbolic and physical tools) plays an important role in human perception and in education. As Carl Mitcham [4] reminds us "artifact design is what constitutes the essence of engineering". Therefore, in the next sections of this essay I devote my attention to the role of technologies in human perception and learning and, hence, in education.

3. PHILOSOPHY OF TECHNOLOGY AND MEDIATED ACTION

Almost seventy years ago Müller [19], in a article about instrumentation in analytical chemistry, stated that: "There is little evidence to show that the mind of modern man is superior to that of the ancients. His tools are incomparably better". The statement by Müller points to the neglected fact that human experience of our world is shaped by physical and symbolic tools (mediating tools). The concept of mediation and mediating tools could be represented diagrammatically as follows:

Human ⇔ Mediating tools ⇔ World

Questions about the role of technology (artifacts) in everyday human experience include:

- How do technological artifacts affect the existence of humans and their relationship with the world?
- How do artifacts produce and transform human knowledge?
- How is human knowledge incorporated into artifacts?
- What do artifacts do?

Tools play important roles in Dewey's philosophies of both education and technology [20]. In socio-cultural theory and in activity-theory, which is rooted in the thinking of Vygotsky, "tool" and "mediation" are key concepts [21-23]. Miettinen [24] has pointed out the similarities between the thinking of Dewey and Vygotsky as regards tools and mediation.

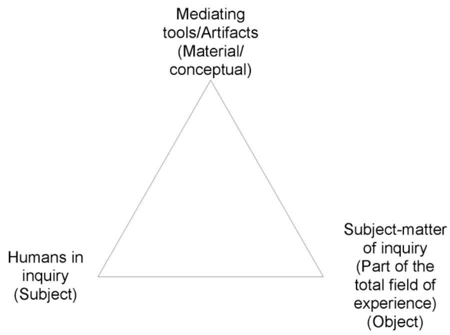

FIGURE 1. A model showing the concept of mediation, adapted and modified from Vygotsky [21] and Cole [22]: the triadic relationship between *subject – mediating tools – object* illustrates that the relationship is transformed by mediation.

The philosopher of technology Don Ihde synthesized non-foundational phenomenology and pragmatism in an approach dubbed postphenomenology [25]. According to him, perception is co-determined by technology. In science, instruments do not merely "mirror reality", but mutually constitute the reality investigated. The technology used places some aspects of reality in the foreground, others in the background, and makes certain aspects visible that would otherwise be invisible [26]. Neglecting the role of technology in science leads to either naïve realism or naïve idealism [26, 27]. Ihde developed the following schematic distinctions regarding mediated intentional relationships between humans and their world:

Embodiment: (Human ⇔ Technology) ⇔ World
Hermeneutic: Human ⇔ (Technology ⇔ World)
Alterity: Human ⇔ Technology (⇔ World)

In embodiment relationships we are normally unaware of the technology. In hermeneutic relationships some kind of interpretation is involved, hence the term hermeneutic. In both embodiment and hermeneutic relationships experience is transformed by the mediating technology. In alterity relationships humans do not relate to the world through a technology, or to a world-technology complex, but to a technology itself.

4. TECHNOLOGY AND LEARNING ENVIRONMENTS

The important role of technology in learning has been pointed out by Nora Sabelli [28], who claims "what and how we learn have always depended on the *tools available* to students and teachers and should change with significant changes in the tools available. … [E]ducators [are] responsible for exploring the profound *pedagogical implications of the changes brought about by technology on the practice of science*" (my italics).

Therefore, I consider that a careful analysis of the role of technology is essential in educational analysis (cf. [29]). The role of technologies in education has not been sufficiently analyzed.

'Microcomputer Based Laboratory' (MBL) activities are examples of the use of "interactive technology" as a tool for learning in physics education [30]. In MBL activities students conduct experiments using various sensors (e.g., force, motion, temperature, light or sound sensors) connected to a computer via an interface. The arrangement provides a powerful system for *simultaneous* collection, analysis and display of experimental data, sometimes referred to as *real-time* graphing. The lab-based curricula "Tools for scientific thinking" and "Real-Time Physics", grounded in physics education research, have proven effective in fostering a functional understanding of physics [31], and in the "experientially based physics" project MBL has proved to be effective in a Swedish context [32, 33], achieving normalized gains of 61% in the FMCE-test (Force and Motion Conceptual Evaluation [34]).

However, I have shown that the same sensor–computer technology ("probeware") used in MBL can also be used in ways that lead to low achievements in conceptual tests, thus refuting claims of technological determinism. My findings indicate that the form of the educational implementation is crucial [32], i.e. we must look at how the intentional *Human-Technology-World* relationship is established.

Nevertheless, as noted by Ihde [26] and Kroes [35], for example, observation is not generally regarded as problematic in positivist approaches and from the anti-positivist perspective, the praxis-ladenness of observations tends to be overlooked. Kroes expresses this as follows: "in [the traditional] view, the physicist is essentially a passive observer in experiments: once the stage is set he just observes (discovers) what is going to happen".

Figure 2 illustrates two common views of technology in education. In these views the *Human–World* relationship is not considered to be affected.

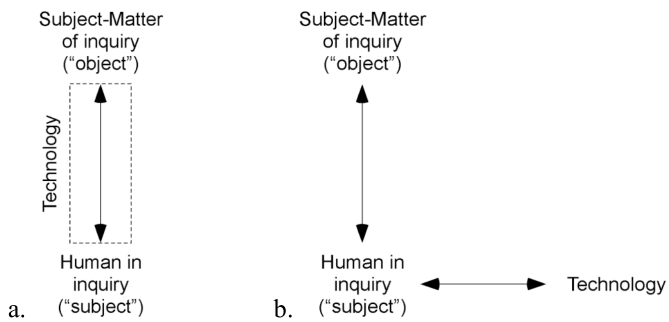

FIGURE 2. a) A 'Transmissive' view of technology, in which technology is seen merely as a vehicle for information **b)** An 'Auxiliary' view, in which technology is seen merely as a provider of information or support.

According to "Variation theory", developed by Marton and co-workers [36], we learn through the experience of difference, rather than the recognition of similarity. In this theory the experiences of discernment, simultaneity (synchronic and asynchronic) and variation are necessary conditions for learning.

It is not possible in this short essay to present a full phenomenological analysis [37, 38] of the role of technology and the *Human-Technology-World* relationships that the learning environment affords [39]. However, I will briefly discuss an example from one of the first tasks in a typical MBL-lab. In this task students are asked to walk a trajectory that matches a given velocity–time graph. While moving the student, and his/her peers, can see the experimental graph produced in *real-time* on the computer monitor (see figure 3). Prior to this, students have solved tasks involving position–time graphs.

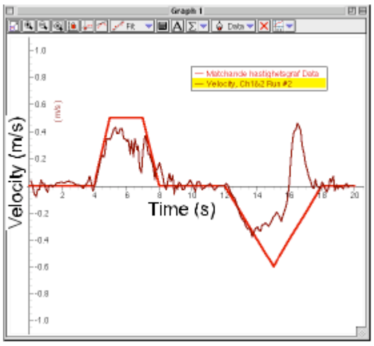

FIGURE 3. Example of a task that students attempt during a MBL-lab. Displayed is a v(t)-graph with a curve that the students are asked to recreate together with an experimental graph produced by a student.

As mentioned above, the way that technologies are implemented shapes figure–background relationships, and the variations that can be discerned. Wartofsky [40] expressed this as follows (p. 204): "I take the artifacts (tools and languages) to be objectifications of human needs and intentions … *already* invested with cognitive and affective content."

What the technology does in this task is to bring velocity to the fore, i.e. it enters in the focal awareness [41] of the students. Other features of the situation, physical as well as non-physical, are not highlighted, i.e. some discernment has already occurred. It is also important that velocity is established as a relationship to objects and events in the world (cf. [42]). In order to complete the assignment, students have to understand this and also they have to make important conceptual distinctions.

I have examined labs that use "probeware" and that have lead to either low or high achievements. In high-achieving labs, the technology is used to bring important concepts and relationships into students' focal awareness, i.e. they are used as a "cognitive tool." A preliminary analysis of the critical aspects of "probeware" use have been presented previously [32] and a paper containing an in-depth analysis based on variation theory and the philosophy of technology is forthcoming (cf. [43])

5. CONCLUSIONS

In this essay I have explored some aspects of the relationships between technology, engineering and engineering competencies on the one hand and, on the other hand, those between education and the design of education. I have presented examples of knowledge and skills from the art and science of engineering that can contribute to the development of education, not only for engineering education but for education in general. According to Cobb *et al.* [11] design experiments should attempt to develop theories that do "real work in practical educational contexts" (p. 13). Engineering research and design has similar aims – theories should prove useful and should do "real work in practical contexts". Engineers have developed theories for design including an awareness of the tensions involved and for dealing with complex systems. Furthermore the art and science of engineering has learned to handle the tension between general theories and the contingencies and particularities of practical situations. Such proficiencies would be of great value in the generation of educational theories and in the development of education practice. Engineering modes of thought have great potential to enhance modes of thought in education and education research.

Furthermore, I conclude that to use technologies to their full potential as learning tools in education, we must understand their cognitive role(s). As mentioned previously, the design of artifacts is an engineering speciality. In this analysis the philosophy of technology can make essential contributions to our understanding. Thus it can contribute to engineering education not only by encouraging critical reflections about *what* kind of skills and awareness are important for sound engineering practice, but philosophy can also contribute to an understanding of *how* technologies can be used in education and in human perception.

Engineering and knowledge of technologies could contribute to the development of the "art of educational engineering" through insights into design and through the awareness of technology. Research in engineering education has great potential to contribute to the "art of educational engineering" and should be regarded as "engineering research".

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