Abstract

Courses in an engineering program are mostly taught in isolation. Designing, the unifying experience of engineering education, is treated a "an art", without guidance about procedure. A single "capstone" course attempts to unify the curriculum, which is almost impossible to achieve. A formal structure can help to unify the experience by showing the relationships among parts of engineering knowledge.

A suitable formal structure to provide a conceptual framework for engineering education is delivered by the Theory of Technical Systems, a section of Design Science. The Theory of Technical Systems shows how one area of science connects to and affects another, and provides a connective structure among the non-engineering subjects. Explicitly teaching the Theory of Technical Systems throughout the years of engineering study should give students a sufficient level of understanding of the reasons for studying each individual subject.

I. Introduction

Engineering design is generally reputed to be the unifying experience of engineering education. Yet in most educational institutions there seems to be a lack of structure to design (a noun -- the appearance and arrangement of a technical object) and designing (a verb -- the process of generating a new or revised technical object). The individual courses that make up an engineering program (mainly the appropriate engineering sciences and humanities) are usually taught in isolation from one another, with little or no cross-referencing. If they refer to design, it is usually as a noun, a description of a small selection of currently successfully operating systems that use the relevant phenomena, and only in relation to those individual phenomena.

The unifying theme should, according to the patterns of the past decades, be deliverable in the form of a single "capstone" experience of designing. This unification is almost impossible to achieve in this way. The heavy capstone tends to buckle the slender columns of the individual course streams from the preceding years of study. The cross-referencing to stabilize the columns does not exist.

Even if design experiences are (ideally) spread across all years of study, designing is difficult to teach and learn, unless a formal structure can show the relationships among engineering knowledge (both about objects and phenomena, and about design processes), the humanities, and societal knowledge. Such a formal structure can also indicate a useful sequence and set of models to underpin the iterative and recursive process of designing. A teacher’s experience of
designing (e.g. in industry) is not enough to be able to teach designing, although it helps. Most academic staff members have no industrial experience to draw on.

In addition, designing is reputed to be "an art", based on inborn talents, and with almost no guidance about how to proceed. Most teachers of design seem to claim one of several alternative approaches: that they only need to build teams, or that a primitive form of apprenticeship is sufficient, or that creativity must be the emphasis, or that a competition is enough. Each of these helps, all of them do not yet adequately describe designing, they are a selection of the elements. These teachers in general do not seem to accept the complexity, and range of object and (mental) design process knowledge that is needed for successful designing. They also think that merely taking part in some sort of design exercise or competition will deliver a sufficient range of object and design process knowledge to enable students to effectively design an engineering system (a product and/or its usage process) in their future occupations. Teaching and learning to design is much more complex.

An old Chinese piece of wisdom credited 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 used to decry lectures and demonstrations, and to advocate only project-based learning. The last of these items is usually omitted.

People learn in different ways, verbally and visually. They learn either for a short time (seconds to minutes), or for longer time spans. They learn best when doing something, especially with coordinated instruction, explanation, demonstration, mentoring and role modeling. Consequently, I would add:

Do all four and I will become competent.

But this implies:
-- Tell me in sufficiently small chunks (elements) that I can grasp, but do not neglect or obscure the context and big picture (relationships);
-- Show me clearly and visibly, both the phenomenon (including designing as a process), its structure, the underlying theory, and its context, not hiding the phenomenon behind high-tech measurement;
-- Involve me by letting me do the tasks under guidance, to give me sufficiently quick success and encouragement, not frustration;
-- And step back gradually, as I develop the insights of the big picture, and the abilities and skills to do the whole job.
This is especially true for designing.

II. Formal structure

A suitable formal structure to provide a conceptual framework for engineering education (and designing) is delivered by the Theory of Technical Systems\(^1\), a constituent section of Design
Science. The Theory of Technical Systems outlines those features that all technical products have in common, in a matrix. The columns describe the organization of the theory into (see figure 1):

- transformation processes and technical process systems, through which an operand consisting of material things (including living matter, such as humans, animals, plants), energy, and/or information are transformed into a more desirable state;
- technical real systems (products) that have the purpose of causing these transformations, when operated under certain conditions, including information, management, and environment;
- properties of those technical systems, organized into 12 classes, see figure 2;
- representation (graphical, verbal and symbolic, including mathematical) of the system and its parts for modeling, communication and understanding;
- origination of technical real and process systems, their life cycle from idea and/or needs (requirements) to final disposal at life ended; and
- evolution of technical real and process systems, their development over time.

The rows show:

- the questions that the areas of the organization are intended to answer;
- individual themes which form the objects of investigation; and
- the disciplines that result from concretization of the knowledge.

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<table>
<thead>
<tr>
<th>Theory of Technical Systems (TTS)</th>
<th>Investigates the nature of technical products and processes (systems), whereby the general nature of technology is treated and can be explained.</th>
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<tbody>
<tr>
<td>Technical process systems</td>
<td>Technical real systems (object systems)</td>
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<td>Properties of technical systems</td>
<td>Representation of technical systems</td>
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<td>Origination of technical systems</td>
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The contents are indicated by examples in each cell. It is noteworthy that the lower (two) cells of the first column ("Technical process systems") shows the engineering sciences and other (codified) knowledge needed to be able to design. The column of "Properties of technical systems" and figure 2 show the societal, economic, environmental and other contexts.
Many more detailed models show factors that are useful for understanding and designing technical systems, see [2,1], e.g.:

-- constituent parts of transformation processes,

-- the typical life cycle of technical systems, especially viewed as important operators of transformation processes,

-- different abstract structures that can be recognized in technical system, and their elements and relationships,

-- various classifications that can be useful for studying and designing technical systems,

-- the classes of properties of technical system (12 classes, see figure 2) and their contents and interpretations -- an essential aid in setting up a design specification (clarifying the problem),

-- various forms of representation of technical systems, e.g. as models of abstract structures -- a useful sequence of models for conceptualizing a novel system to be designed,

-- development (evolution and innovation) in technical systems over a longer period of time.

These can act as check-lists during designing, as guidelines for strategic procedure (as indicated), and as theoretical basis for developing and adopting methods that can be used within the design process. They are particularly important during the learning phases, and become less important as the understanding and skills improve, i.e. for graduated engineers in their early
years of practice, until that design process knowledge is so well internalized (learned) that it appears as "tacit" knowledge, and can then even be denied.

The Theory of Technical Systems provides several forms of meta-knowledge. It shows a connective structure among the engineering sciences -- showing how one area of science connects to and affects another. Designing (e.g. an internal combustion engine) can only be successful if the needs and requirements from thermodynamics, strength of materials, mechanics and dynamics, manufacturing methods, societal needs, economics, and other areas are balanced -- see the classes of properties of technical systems, figure 2. With these properties, the Theory of Technical Systems also provides a connective structure among and to the non-engineering subjects -- the reason for including an exposure to the humanities, interactions among technology, science, arts, sociology, psychology, etc. But this demands that all courses are cross-referenced to one another -- a difficult task for the teachers and for the administration.

III. Theory of technical systems as a teaching tool

Explicitly teaching the Theory of Technical Systems throughout the years of engineering study, at an appropriate level of detail, should give students a sufficient level of understanding of the reasons for studying each individual subject (course). For best effect, each such contributing course should also refer to the Theory of Technical Systems to show its place in the structure, and to provide reference points for its significance.

Using this structure, the purposes and constraints of designing (for any real product and/or its usage process) are also easily explained. Because designing must accommodate all phases of the life cycle, and must provide an adequate (preferably optimal) set of properties for the product, a certain amount of structuring of the design process is also preferable. This involves (initially formalized) design methods. They are especially useful for the phases of conceptualizing a product, whether it is a newly designed or a radically redesigned (innovative) product. Conceptualizing should be done before any layout is attempted, especially if computers (CAD/CAE) are to be used for representation of the system being designed.

It is mainly during the educational experiences that students can be exposed to formal design methods, and in this way can find time and encouragement to fully use the interaction between formal methods and their intuitions to improve the resulting products. Hoping to introduce design methodology into industry is almost doomed to failure, engineers in active practice have neither the time, nor the management support to learn the offered methods. The Theory of Technical Systems is currently the best basis for unifying engineering education, and for teaching and learning designing. It has been used with significant success at several universities world-wide.

A significant impact on the design capability can only be expected after a substantial period. German engineering students began to be educated in systematic design methods (e.g. according to VDI 2221) in about 1975 -- the improvements are only now becoming obvious. Fantasists become visionaries only after their ideas have begun to be accepted.
Bibliography

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