TEACHING ABOUT METHODS -- COORDINATING THEORY-BASED EXPLANATION WITH PRACTICE

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Abstract

Engineering curricula have mainly covered object knowledge, theories about phenomena and objects, especially in the engineering sciences. Humanities have been attached as external contributions. Another form of knowledge, process knowledge, is also needed for engineering. An integration is necessary in engineering education, the other contexts and influences of engineering must be made clear in a unified way.

This is now possible on the basis of Design Science and engineering design theory. These developments provide a theoretical basis for design process knowledge, which shows how and with what procedures and methods the needs of society can be negotiated and captured.

The necessity for explicit teaching of methods, and of engineering design process knowledge, is urgent. Methods can be coordinated with stages of engineering design processes, and specific methods give systematic instructions for incorporating the contexts of engineering into the problem statements and evaluation criteria. Problem statements must be reviewed, and solution proposals adapted to circumstances.

Introduction

Engineering is different in certain aspects from science, arts or other activities. The main difference for professional engineers is the duty to solve open-ended problems:
-- by interpreting the real and perceived needs of (individual or corporate) members of society;
-- by searching for alternative solutions using scientific, experiential, intuitive and other knowledge;
-- by making decisions under great uncertainty, but employing some strong analytical tools;
-- by providing specifications for implementing solutions, in the form of proposed services (processes) and associated products, to satisfy some of the needs, including (at times) supervising the implementation;
-- usually with the obligation to deliver a workable (possibly optimal) solution under time and cost limitations.

In these efforts, professional engineers are almost always helped by (and work as a team with) other engineers and specialists in associated fields. They are also helped by technologists, technicians, skilled and less skilled manual workers, administration, etc. They usually act within a commercial organization (including consulting), and must therefore consider company policies, economics, socio-political reality, etc.

These activities are usually termed engineering design, sometimes just called “engineering,” where they lead to products (objects, including software or processes). Engineers cannot themselves have all the required knowledge for any product, they must obtain advice from others and have consultations with specialists, both of whom are regarded as team members. Engineering mostly involves team work. Nevertheless, the responsibility to supply the manufacturing and implementation instructions for the most suitable product or process rests with the engineering designers.

Engineering design solutions to problems (reflecting needs) can be characterized in several different ways, e.g. according to complexity of the solution proposals, difficulty of designing, technical sophistication, novelty, addressed market, etc. These aspects are in part correlated to our impressions of creativity, which is
mainly perceived in the proposed solution to the problem.

**Current Situation**

Engineering curricula at universities in the recent past (and today) have tended to cover strictly *object knowledge*. This consists mainly of theories about usable phenomena, processes and objects, especially in the engineering sciences, and these consequently tend to be analytical in their approaches. They are thus firmly based in mathematics and the “pure” sciences. This has led to a false “recognition” of engineering as, and even equation to, “applied science.” That engineering activity requires much more than a mere application of science is suppressed. Synthesis, the essence of engineering activity and creativity, gets short-changed.

In addition, the teaching of mathematics is usually done in isolation, as a relatively “pure” subject, rather than as a set of useful tools. Some useful tools for synthesis are thereby neglected, e.g. order-of-magnitude calculations, error assessment and propagation, etc.

Some connection to experiences is also presented in many courses, but is mainly (falsely) assumed to be readily available from industrial practice, when graduates enter employment. It is unfortunate that this practice-relationship comes too late in the development of future engineers. It is then left to an organization that has a different primary goal, and is not concerned with education. One frequently hears complaints that engineering curricula are too abstract and mathematical.

Humanities have been attached to engineering curricula as external contributions from other departments, usually in the form of service courses, and as electives. Contextual connections to engineering and the engineering sciences is mostly lacking. Students tend to perceive these courses as unrelated (to engineering) and unimportant trimmings -- hairy (or bald) professors talking around their own pet subjects in a world-remote and isolated way, without ever connecting to other (more directly real) experiences and knowledge.

The engineering sciences, in this context, follow the conventional divisions of physics and other sciences. Principles of the various phenomena are presented and analyzed. The fact that the same result (e.g. an amount of mechanical rotary energy delivered at a certain place and time) can be achieved by using several principles from different regions of physics and/or other sciences, or their combination, is never brought to consciousness. Yet this is the very essence of synthesizing, and of finding appropriate and creative solutions to a problem.

**Process Knowledge and Creativity**

One important factor that has been largely neglected to date is that a second kind of knowledge exists, and is used. This kind of knowledge relates to procedures, methods and methodologies, *process knowledge*. It consists of a set of steps, stages, phases or items which should be considered in general, when a (usually open-ended) problem is to be solved. Usually, steps are either undefined or not acknowledged.

The typical steps and their procedural contents (and needed object knowledge) can be recognized at several levels of action -- from elementary operations (hierarchical level 5 according to), and activities of general thinking (level 4), through problem-solving (level 3), and design operations (level 2), up to the complete design (or re-design) process (level 1). They cannot be regarded either as compulsory (steps can be omitted), or as quasi-linear prescriptions to guide the problem-solver. Almost all problems are too complex, and human mental capacity too limited, to be solved directly; iteration (repeating revision) and recursion (breaking the problem down into smaller tasks) are always needed. Humans also tend to use judgment and intuition to guide their work, in order to expend minimum effort. A problem-solving activity therefore may appear to the casual observer to be random. Nevertheless, guidelines for procedure are always helpful, at least as a check-list for ensuring completeness of the task, and to categorize the (written, drawn, etc.) records of activities.

Considering level 3 of the hierarchy of designing operations, a typical and composite definition of steps for problem-solving, can be listed. These constitute a generally applicable strategy, containing various tactical moves. It must be adapted by the problem-solver to the actual problem, the situation within which a solution should be found, the capabilities of the problem-solver, etc. Other (tactical) methods and tools can be incorporated into the procedure, as needed.
Main Operations:

3.1) elaborate the assigned specification
prepare, self-motivate “I want to and I can” -- read the given problem
define the situation, define the stated problem (possibly question the definition)
-- who is (or should be) involved? (actors)
-- what things are (or should be) involved? (props)
-- what happened (or should happen)? (action)
-- when did it (or should it) happen? (scene)
-- where did it (or should it) happen? (scene)
-- why did it (or should it) happen? (cause)
-- how serious is it (or will it be)? (effect)
gather information about the problem, and the properties that the solution must have
-- elements (hardware, software, firmware, processes)
-- relationships (internal, cross-boundary)
-- structures
-- taxonomies
-- correlations
state the goal
3.2) search for solutions
find candidate processes and objects (hardware, software, firmware) for solving the problem
-- literature
-- experience
-- prior art (e.g. patents)
-- generate ideas, by intuition, imagination, incubation, illumination
prepare the plan, and keep it under review
explore -- understand the real problem
take action to collect, classify and record
3.3) evaluate, decide
select criteria for choice
select the most suitable solution
take action to record
3.4) communicate the chosen solution
pass information to next more detailed stage, implement, make and test

Auxiliary Operations:

3.5) provide and prepare information
3.6) verify, check
test the solutions
-- mental experiment
-- order-of-magnitude calculations
-- analysis, simulation
check for possible improvements, especially of unsatisfactory elements
look back -- establish what has been learned -- process and object knowledge
3.7) represent
graphical, verbal, symbolic/mathematical, combination

Creativity (accomplished by a human, and judged according to the designed result) is predicated on a combination of necessary (but not sufficient) conditions. These include sufficient object knowledge, process knowledge, judgment, open-mindedness, care and attention, motivation, communication abilities (in words, symbols and pictures), a suitable stress level, and a sense of ownership of the problem.

It has been shown that creativity is normally enhanced, after procedures have been learned, by using systematic methods. The possible solution fields can be extended by systematic search. Creativity and the use of systematic methods are not incompatible, they are mutually supporting.

The renaissance person, rather than the research scientist, should be the role model for our engineering students. Wide-ranging interests, keen observation of complex situations, willingness to reserve judgment,
tolerance and flexibility, coupled with extensive expertise in the field of endeavor should be the educational goal.

**Mental Properties, Maps and Learning by Doing**

Each person, during the history of his/her lifetime, develops a unique mental map of the acquired knowledge, and of the many-layered relationships among the items of (object and process) knowledge. The nature of this mapping is unknown, and hidden in the vast complexity of cells and neurons within each brain.

The judgment and intuition required for designing and problem-solving (mentioned above) needs to be developed. Merely dropping a learner “into the deep end” of a situation can result in that person learning his/her own “best” procedure, which is itself a desirable aim. Yet that “own best” procedure can just as easily result in blocking, a deficiency of capability, as it can for producing good problem-solving capability. A more controlled learning environment is needed for optimal learning by the largest number of students.

This can best be accomplished by guided practice under conditions of relatively low stress and threat -- where failure is acceptable. In the learning stages, a good explanation of the ideal procedure to be followed is needed (e.g. the list of problem-solving steps above), at a level appropriate to the task and the learner. This good explanation can be given before, during, and/or after sessions of practical application, preferably at all three times and repeatedly.

It is in the nature of process knowledge that an explicitly presented set of steps and their execution is learned, and by repetition it is internalized. Eventually, this results in a stereotypical behavior where the learner no longer needs to think about the steps and procedures. What has been known for centuries about training (e.g. for sports and manual activities) is equally valid for mental activities. This is the essence of “learning by doing” -- being active on a problem whilst being coached for optimal performance on the basis of good (preferably theory-based) knowledge of the requirements for optimal performance. Having learned an activity, the subject can usually no longer fully explain what he/she is doing, the activity has become intuitive and stereotypical. But this indicates that examining this process knowledge becomes difficult -- it can only be assessed by implication, from the records made during solving an “object” problem, the results.

During learning, before the procedures have been internalized, the levels of performance and creativity generally reduce. This is another similarity to physical training. Yet once the procedures are even somewhat familiar, a practitioner can change from normal intuitive/stereotype action to emergency action, and thereby to solve unfamiliar problems by deliberately using systematic methods -- and be at least reasonably effective.

Processing activities (designing and/or problem-solving) need to be done on an objective problem --in other words, practitioners not only need process knowledge which is explicitly used and/or internalized-stereotypical, they also need sufficient and varied object knowledge relevant to the domain and/or speciality in which they are designing. Preferably, this object knowledge should include awareness (in lesser depth) of many other related, or even distant, subjects and phenomena. This awareness should include topics about the economic, cultural, social and environmental context in which designing must be done.

These paragraphs should act as some of the applicable guidelines for our teaching activities, and for curriculum development.

**Integration of Knowledge Types**

An integration of engineering sciences, experience and the humanities is necessary in engineering education. The social, cultural, economic, political and other contexts and influences of engineering must be made clear in a unified manner. This treatment should reveal the elements of this socio-technical systems, the many and varied relationships among the elements, the effects of complexity, of multiple opinions, etc. It should also reveal the actual occurrences and their theoretical foundations, and not just as simplistic quasi-linear models of phenomena.

Neither capstone design courses, nor competition projects can, in general, fulfill these requirements. They
tend to be informally organized, without clear goals, and lacking comprehensive coverage. Whilst the exposure
to design problems tends to be valuable, it is not sufficient.

The needed integration of object knowledge and process knowledge has now been made possible on the
basis of Design Science and the associated developments of engineering design theory. These develop-
ments provide a theoretical basis for the design process knowledge. In particular, they show how and with what
methods the needs of society can be negotiated and captured. Among other items, these developments define
the classes of properties of technical systems, for which we should be designing -- design for X. They can also
explain in broad terms what effects these systems are likely to have on society and the environment.

The necessity for explicit teaching of methods for designing, as part of engineering design process
knowledge, is thus more urgent, but can also provide the contact to the humanities (e.g. through the properties
of technical systems). Methods can be coordinated with stages of engineering design processes, and some
specific methods give systematic instructions for incorporating the social, cultural, economic, political and other
contexts of engineering into the problem statements and evaluation criteria. Yet both must be augmented by
practical advice in the form of heuristics, which reveal what values and procedures can usefully be used.

It is also clear that perceptions of problems can change over shorter or longer time periods. These chang-
es can occur by acquisition of additional knowledge, by social or political factors (including power pressures),
and other influences. Problem statements must be continuously reviewed, and solution proposals adapted to the
changing circumstances. Flexibility and acceptance of change must be maintained, whilst all available heuris-
calics are used to design the world-class products needed for future survival.

Closure

The distinctive feature of engineering is the duty to solve open-ended problems, usually as a team, to
deliver a workable solution -- summarized as designing. Designing obviously requires object knowledge, about
the phenomena that can be used to fulfill the required working and societal functions. This range of knowledge
should be connected to experience, including useful heuristics. In addition, designing requires process knowl-
dge, about design processes and open-ended problem solving, including methods and tools to assist synthesis.
Systematic methods and tools can augment the intuitive procedures. Such methods must be learned in a benign
environment, by combining explanation (preferably theory-based) with problem-based activity -- until the
methods become internalized and maybe even intuitive/stereotypical. They are then also available as emergen-
cy action directives. Explicit teaching and learning of appropriate methods, especially if they are based on
Design Science, provide a ready means of integrating the physical (engineering sciences) and societal (humani-
ties) object knowledge with process knowledge to approach a renaissance outlook on engineering.

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