Educational theory and engineering education practice:
A generalisable description of the design of a lab course on
how to investigate electrical circuits

Dr. Henk Vos, PhD Phys., PhD Ed.Sc., Dept. Electr. Engineering, University of Twente,
Enschede, Netherlands.
E-mail: h.vos@ewi.utwente.nl

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Introduction

Newton's laws describe some very general principles of the motion of an automobile car and
their quantitative relations but do not prescribe its design. For instance, a vehicle does not
necessarily have four wheels, but based on Newton's second law it should have an engine that
provides a force. Once a design has been made, theory helps in the analysis of the
performance of this new design (as in computer aided design) but the vehicle still will be
tested in practice. A good car design will stimulate other companies to design a similar car
based on the patents they possess.

Likewise, psychological and educational theories describe some very general principles of
learning but do not prescribe the design of a course. For instance, a course does not
necessarily include lectures, but based on psychology the students should have a motivational
drive to execute the tasks given to them. Theory maybe of use in the analysis of a course, but
a course should be tested in practice. Some courses turn out to work well and could be used to
improve education elsewhere. If one wants to improve education by disseminating good
practices, several ways can be followed.

Burckhardt and Schoenfeld e.g. discuss several methods and focus on evidence-based
educational improvement, and research needed for that, so that observed educational
phenomena can be reproduced elsewhere, in other tasks, topics, courses, programs, by other
designers, teachers, and students. However, it may be that good teaching in one situation is
not good in another. Also it is not clear what exactly should be transferred. It is e.g.
questionable whether one can provide evidence that specific design rules are responsible for
good practice: good practice can be the result of several design rules.

De Graaff and Kolmos e focus on the dissemination of problem- and project-based learning
and the research on change needed for that. This research is heavily needed because it turns
out that dissemination of good practices is difficult: there is much resistance to overcome. A
generalisable description of the characteristics of education may help in both cases to describe
good practices such that others can make use of those.

Descriptions of educational principles are often phenomenological (like the description of
position and velocities of planets in Kepler's laws) and thus applicable to similar situations
only (the orbits of comets e.g.). A more generalizable description needs more abstract and
fundamental concepts (like acceleration, i.e. the change of velocity). Also a comprehensive
description of the educational phenomena is needed (an acceleration always comes together
with a force, without the description of the force motion cannot be fully understood). A first
step to this in education is an identification of the central concepts and independent variables involved. Thus the main question in this paper is which concepts and variables describe education (i.e. teaching and learning) in a general way.

Why does research on education not help much? The first problem here is that educational research is split up and based on mini-theories from certain psychological or educational "schools". Other "schools" use other terms, other concepts and sometimes even other measurement instruments. So for a comprehensive general theory one has to combine research from different "schools".

Other problems arise from the difference between educational research and engineering education practice. A small intervention that works well in a randomized treatment-control group design of educational research in a class of psychology students, may have unforeseen effects in practice because then other variables come into play. So research that can be of use in practice should also start from educational practice: first bottom-up and only then top-down.

When a generalizable and comprehensive description of education has been found, this could enable teachers to identify the aspects of education they had not thought of and that possibly could interfere with their practice. Like e.g. that in practice the students of a class will differ in preferred learning methods and that this entails that the instruction and tasks given to the students have to serve them all, good, moderate, and weak alike. Such a description of education should also tell the teacher how teaching a certain topic could differ with respect to its learning effects and how negative effects may be circumvented. It should give insight in the characteristics of education such that a teacher can use ideas from good practice elsewhere more easily and implement them in his own teaching. Several considerations are of importance here.

Learning is like acceleration that changes velocity: the activities and capabilities of the students change because they are going to act differently. The engine here is a motivational drive. The variables should describe the way the students become motivated to put effort and time in learning. We focus here on the drives that can be influenced by the teacher, not those that come from other sources like the educational system as a whole, such as a high tuition fee.

The variables should describe the way learning of the students is controlled and facilitated by the teachers, thereby making use of the environment of the class, library, labs, instruments, organization of the school, and the surrounding community. We focus here on the factors within a course that control the goals and the activation of prior knowledge of the students. We restrict ourselves here to cognitive development and neglect personal development.

The co-operation of students with other students in class (asking, observing, explaining) is considered here as reciprocal teaching, thus neglecting social interactions. Also the interaction of courses in a curriculum is neglected (e.g. other courses as rivals for the time of the students).

The variables should describe the activities the students carry out in a course (the tasks), and the lasting effects of these activities (learning). We focus here on the learning that takes place during a course, including grading.
In this research we try to identify basic concepts and variables of education. The approach for this research was to compare good practice in engineering education and general theory of education and psychology. First, two general levels of functioning of engineers were identified. Second, four variants in functioning of engineers were identified, that are relevant for teaching and learning in general. Thus, from searching literature and relating this to educational practice, an abstract conceptual framework was identified that could consequently be used to theoretically describe, relate, and explain the learning in a course that was an example of a good educational practice. Finally, this framework was used to analyze learning of low and high level skills.

The course studied was a lab course on how to investigate electrical circuits, with high demands to the students with respect to insight and a systematic approach. This course was redesigned and the pass ratio raised from about 50% to a more acceptable and stable 80% while the same high demands were met. Thus the course was a candidate to be good practice in education. This course has been well documented (see chap. 4 and Appendices A through F. Also internal documents, in Dutch, are available from the Educational Center of the University of Twente). The concepts and variables identified earlier should convincingly describe the aspects of the course relevant for dissemination.

In the following first two levels in functioning of engineers (and students) will be presented. Next four variants in functioning, teaching, and learning. Then the course will be presented: why is it an example of good practice in high-level learning and what are the educational phenomena found. Fourth, the design of the course will be presented in terms of the comprehensive conceptual framework of four basic educational variants describing learning on the higher level. Finally, the application of the foregoing on both low and high level learning will be discussed.

An overview of educational design variables in good educational practices on two levels is presented. This overview makes clear that good educational practice on one level, can be bad practice on the other level. It will be discussed what conflicting situations can be met when one wants to teach on low and high level skills at one time. Also what research still is needed before the conclusion can be drawn that the conceptual framework of two levels and four variants provides a generalizable description of educational practices and contributes to design of engineering education.

**Two levels of functioning of engineers**

Once I heard an engineer say: "I have no knowledge in my head. Only when I have to solve a problem, some knowledge emerges, and I can start to work on the problem." Somehow engineers have the skill to activate knowledge when needed. This is a skill that controls an activation of technical concepts and skills like ciphering or doing complex calculations. The engineer knows what knowledge he needs, and when and how knowledge comes into his head. The knowledge and skills of engineer are clearly of different types.

The first type has to do with knowledge like what a battery or a norm is, with skills like calculations, typewriting on a computer, solving end of chapter problems, recalling definitions or norms. With feelings like an electrical shock (that causes engineers to be more careful) or being satisfied because a reward is given for some task. With information processing, like being able to read data, graphs, and schematic information. Skills of this type can be
demonstrated to a student, and have an observable outcome. Knowledge, skills, feelings, and processes can be directly observed, and also expressed and demonstrated.

The second type has to do with skills like planning, sound reasoning, doing research, design, or approaching problems in a systematic way. With knowledge like insight, overview, coherence of knowledge, with knowing what you do not yet know but need to know. With feelings like intuition, feeling that the solution is near, or that you are on the wrong track. With processes like critical reading, and being able to understand the consequences of data. Knowledge, skills, feelings, or information of this type are more difficult to express, explain, or demonstrate, and some not at all. Knowledge, feelings, or information will be referred to later, now we concentrate on the skills of the two types.

Skills of the second type are often called higher order skills. They include soft skills like cooperation, oral and written communication, and the like. Others, especially educationalists, relate these skills to deep understanding and deep processing in learning, i.e. a deeper level. It has to be stressed, however, that these skills are no more or no less important than the skills of the first type. They are just needed in other situations. In this paper the skills of the second type will be called higher level skills, because putting high demands to the students usually relates to these skills. Also, a cognitive conflict between two people or between two ideas of the same person, requires to take a position above the conflicting ideas, i.e. a higher position.

In psychological theory Vos 4 found concepts that include these two types of skills, cognition and metacognition. In the past metacognition was not distinguished as a part of cognition, nor as a part of intelligence to which cognition is strongly related. Simon and Kaplan 5 described cognition on an abstract level as the capacity to use intelligence in executing tasks, or the capacity to execute cognitive tasks. De Groot and Van Peet 6 understood cognition as equivalent to cognitive functioning. By this definition, all combinations of psychological functions can play a role, like observing, memory, thinking, making a sound choice and deciding, but also intuition and processing emotions. Cognition can be the act or process of knowing, including both awareness and judgement, and can also be a product of this act 7.

Knowledge of metacognition was first developed in research on memory (see e.g. 8). Flavell 9 first used the term metamemory, and later the term metacognition. Metacognition involves “active monitoring and consequent regulation and orchestration” of cognitive processes to achieve cognitive goals, according to Flavell 10, 11. Monitoring, regulation, and orchestration could take the form of checking, planning, selecting, and inferring 12; self-interrogation and introspection 13; interpretation of ongoing experience 8; or simply making judgments about what a person knows or does not know about how to accomplish a task 14,15.

Metacognition can be described as cognition about cognition. Since cognition can be considered as a faculty or capacity, as a process, or activity, as well as a product this process, so metacognition can. Literally metacognition means: beyond cognition. However, metacognition is considered to be a part of cognition in general. Distinguishing metacognition from cognition entails that the meaning of cognition has to change. The higher (or deeper) level of cognition is called metacognition, the lower (or superficial) level of cognition is the new meaning of the term cognition here. The higher level of functioning of engineers mentioned earlier, can be identified with metacognition, the lower level with cognition.

Again, the terms higher, deeper, or meta, originate from specific viewpoints but involve no qualification, just a description. The characteristics of metacognition are interesting. My
experience is that where something goes wrong in education, it is related to a metacognitive variant. All metacognitive variants interact strongly (are strongly correlated) so training one helps the others to develop. Developing ("training") metacognitive variants is possible, takes a lot of time, and is difficult to control.

**Four variants in tasks and learning**

An example to illustrate the variants of metacognition is that readers know that they have read something before but may not remember where and when right away (feeling of knowing, a metacognitive experience). Another is that readers start to skim an article (reading is supposed to be part of a task) in order to find out what are the most important parts (a metacognitive goal or task), by looking through the headings, the first paragraphs of each section, and the pictures (a cognitive skill) and relating their meaning to each other (a metacognitive skill or strategy). The readers can get the feeling that the article is easy to understand (metacognitive experience: feeling of difficulty), but that sometimes the heading of a section (metacognitive information) does not correspond to its content (what shows understanding, i.e. metacognitive knowledge).

Another example (in learning) from Flavell 16 follows. Suppose that you prepare yourself for an examination. "You wonder (metacognitive experience) if you understand the chapter well enough to pass tomorrow's exam (assessment of knowledge and skill), so you try to find out by asking yourself questions about it and noting how well you are able to answer them (metacognitive strategy, aimed at the metacognitive goal of assessing your knowledge, and thereby, of generating another metacognitive experience)". Flavell called the variants metacognitive strategies (or skills), metacognitive tasks (or goals), metacognitive experiences, and metacognitive knowledge (or beliefs).

Metacognition is considered to be a general phenomenon that includes four variants just as cognition. Some relevant examples of these variants are that persons can know some or all of the features of their problem solving approach (metacognitive knowledge); can keep the goal in mind in handling a task (a metacognitive strategy); can more or less explain, i.e. model, how they reason (a metacognitive task when the instruction is considered, or metacognitive information when the result is); and can feel that they know something although they cannot recall it at that moment (a metacognitive experience).

The descriptions found show that it is possible to separate the phenomena of cognition and metacognition in two ways. First the contents or objects differ: metacognition is about cognition, i.e. about mental processes, cognitive tasks, and includes the accompanying experiences. Human beings somehow must be able to "observe" these processes and experiences that cannot be observed directly otherwise. When we take this description serious, we can subtract metacognition from cognition, leaving 'cognition'. This leaves for 'cognition' as objects the concrete things in the real world via the direct, unprocessed, observations and memories thereof. 'Cognition' involves observing and handling the things in the world. These things not only include material objects, persons, events, physical phenomena, etc. but also signs in the forms of words, figures, diagrams, and graphs.

Second the functions of cognition and metacognition differ. The function of 'cognition' is to solve problems, to bring cognitive enterprises to a good end. Its function is behave in an intelligent way. The function of metacognition is to control a person's cognitive functioning in
solving a problem: starting a task or leaving it, focusing the execution of a task on its goal, and evaluating the outcome of the task and the actions of the person. As an engineer will understand, controlling here includes monitoring of one's knowledge, activities, feelings, information, making decisions by comparison with a 'norm', and regulating one's cognitive functioning.

Metacognitive experiences are combinations of cognition and affect, or in the present definition: affects on cognition. They influence e.g. the handling of tasks. For instance, the feeling of difficulty may lead a person to start a task or not. Both metacognitive knowledge and experiences can lead human beings to select, evaluate, revise, and abandon cognitive tasks, and the strategies used in the execution of the task. This suggests that metacognitive thoughts are deliberate, planned, intentional, goal-directed, and future-oriented mental skills that are used to accomplish cognitive tasks. Thus many researchers use the label metacognition for conscious and deliberate thoughts that have other thoughts as their object, but others include also nonconscious processes as is done in this article.

Cognition in general thus is a phenomenon: it cannot be measured itself, but the four (independent) variants of it can, here distinguished in knowledge, skills (equivalent to actions), information (equivalent to task, instruction), and feelings. In cognition two levels can be distinguished: metacognition and 'cognition'. The view in this paper is that all four variants and both levels are needed to give a complete description of tasks and learning in specific cases. If one or more variants are not specified in a description of education, it is not guaranteed that the results of that education can be replicated.

Teaching and learning

Learning

Before two levels of learning are introduced it is good to bring in mind that one can distinguish learning new skills, improving skills, and unlearning skills.

Learning new skills includes at least 4 basic types of learning from the viewpoint of the interaction between a teacher and a learner. These four all are important in the practice of learning, but some get more attention then others. These four strategies of learning new skills are independent exploration, guided exploration, imitation, and formal learning.

Independent exploration is how children start to learn. This is also the way students learn to handle mobile phones, computers, and the Internet. Some people call this strategy "playing" with instruments, tools, or formulae, and no teacher is needed. Such exploratory actions lead to learning of new skills and insight, mostly by finding, less by searching, and by trial and error. Only when the students get stuck, they look through the manual or guide.

Guided exploration, the second strategy, is the case when the teachers or the guide give hints. Guided exploration often involves strategies to be learned, like in learning design. Design cannot be described as an algorithm or 'cookbook', but by heuristics only. Learning to cooperate in team-projects of increasing demands and varying composition is another example, especially when the teachers present some notes on how to communicate and organise decision making.
The third strategy is learning by imitation. Here the teacher gives a demonstration of the skills needed. Tutoring hours where calculations are demonstrated or example problems are solved are of this category. In industrial training the students observe what goes on in a company and they may learn to be an engineer by imitating behaviour that they like.

Fourthly, new skills can be learned by getting instructions, carefully reading instructions, and step by step carrying these out. This is often the main focus in formal learning. The example of learning how to use a computer can teach us that often this track is available but not followed. Learning to type blind with ten fingers is of this category, but also a lot of independent formal learning, e.g. by students who are not able to attend classes and have to study at home. The procedure here is basically that students repeat skills they already know and combine these with other skills to construct new combinations step by step.

These are four strategies to learn new skills. To improve skills that have been executed once, the skills have to be repeated. Most people know that by repeated recall of knowledge, it becomes easier to recall that knowledge again. Often the teachers include skills that are already learned in later tasks or courses. In this way learning is not the explicit goal of that repeated use of skills and may remain implicit for the students, and thus unaware. Becoming better by repeating skills, be it in executing professional tasks or in education, takes place in phases.

When a specific skill is practised repeatedly the students will make fewer errors, their performance will become more fluent, with less hesitation. When the skill is applied to more situations, to other cases, on more occasions, and to various objects, the skill becomes generalised. An example is calculating the volume of a cube, a house, or a sphere. By further repetition the skill becomes abridged: less intermediate steps are needed, like in calculations when less lines are needed and several steps can be taken at once in ones head. Finally, by explaining the skill to the teacher, discussing it with fellow students, or by writing about what was done, the skill is executed in the mind and may be done in an entirely mental way as a real expert is able to.

Also nonconscious processes improve skills. For instance, it is found from research that during sleep the brain is active, and this activity not only helps to store daily experiences into memory but also can improve skills. When students have tried to solve certain problems one-day, they have become better the next day after a sound sleep. Such processes will not be considered further.

Another important process is unlearning skills. When skills are executed in the wrong way, they have to be replaced by other skills. This unlearning is not easy, sometimes requires negative experiences, punishment, or even a new start, just like some professional students of music have to do finger exercises anew. “Back to the basics” may be needed to unlearn hampering knowledge.

In learning new skills, many errors are made. In exploratory learning such errors are automatically followed by other tries. In other types of learning feedback from the teacher or from peers might help. For instance, in formal learning tasks are given to the students in the form of instructions (including accompanying information). The students become more or less motivated for the task, have a goal in mind, and activate prior knowledge that is needed. The students orient themselves on how to do the task, and execute the tasks.
Teaching

The teacher might check the product, or evaluate the execution and the orientation, and give feedback to the students about what is good and why (green pencil) and what could be done better next time and how (red pencil). These are functions the educational system should fulfill, in order to let the students learn new skills (cf. Table 2). It must be stressed that these functions can be fulfilled by either the teachers (teacher-guided learning), or by the students themselves (student-regulated learning), and even peers can help (e.g. working in pairs, and peer-assessment).

A good teacher knows that the students should learn to execute tasks by themselves. So in cases where guidance from the teacher in the beginning is needed (scaffolding), this guidance should be diminished later (fading). Students should learn to check the products of their actions by themselves: that is what the workplace will require. So students should learn skills in phases: first learning the new skill, than practicing it in new situations, and finally applying it to new situations when not asked to (transfer). Teachers or peers should provide feedback on the moment that the students are in the position to improve their skills, just before they need them again (just in time feedback).

Activities in tasks and learning

It goes without saying that what students want differs from what the teachers want. Some students are learning by doing what is told them to do in order to pass the tests, others really want to be able to measure or calculate things by themselves, still others want to really understand the subject matter, or even to control their learning themselves. Students who are ill are in the last category: they are forced to control their learning themselves.

So the students have their own motivational drives to learn, they set their own goals, and their prior knowledge is known by themselves only (unless it is forgotten). All these variables interact, and they also interact with an expectation about the success of the tasks, about the ability to handle the instruments that are needed, etc. To clarify these interactions a course is now described in terms of the higher of two levels and the four variables on that level.

Redesign of a course (design experiment)

As said, the course studied was a lab course in Electrical Network Analysis (ENA), which was redesigned. Why can this course be considered a good practice of teaching and learning? There are several reasons for this. The redesigned course could be compared with the earlier course because data were available about the four years before and four years after the change. The passing rates were raised from 48 % to a stable 79 %, with the same high demands on the students. The students were graded on their ability to use a strategy for doing investigations, and on insight in the topic, what included the skills to calculate and measure the quantities needed. The total time spend by the students diminished slightly although the number of pages of the lab guide nearly tripled from 22 to 61 pages. The time that was spend by the TA’s on explanations and help diminished considerably. There were no changes in the lectures or tutoring hours.

It was reported earlier which data were used to exclude alternative explanations of the increase in the passing rates: (a) the students after 1987 were not better than before, thus they
belong to the same population; (b) the students were not trained in the same cognitive skill, thus no mastery learning was the case; (c) the time spend on the course diminished slightly with respect to earlier measurements; (d) the lab course did slightly better than before discriminate between good en weak students, so the students were not dragged through the course by assistance or otherwise; (e) no other changes in the curriculum could attribute to the increase (no environmental effects).

So this course can serve as a good example of teaching high level skills to the students in a reasonable short time (nine weeks), effectively and efficiently. The course ran in parallel to lectures where the theory was explained and tutoring classes where the students were trained to solve calculation problems. The redesigned course was divided into three parts or domains, each consisted of three sessions of 4 hours work.

The content of the first three sessions, the introductory part of the lab course, was input-output systems in simple electrical networks, their elements, and the methods to measure characteristics of these elements like the values of their electrical resistance and capacitance (RC-circuits). Also the characteristics of input signals, from sources, and output signals (responses), into loads, were treated, like their form and frequency, the phase difference between the input and the response, and the power transmitted by the signals. The forms of the input signals used were square wave and harmonic.

In the next three sessions the signals were described as functions of time, the reason why this part of the course was called the time domain. After definitions of network properties like linearity and time-invariance were given, the students had to detect linearity in circuits and to construct responses by superposition. Differential equations were used to calculate step- and impulse responses, which were also determined experimentally. With the aid of the response to an impulse as an input signal the mathematical concept of convolution could be used to calculate responses to other signals.

Finally in the last three sessions the signals were described as a superposition of harmonics, in which way the signals became a - for the students difficult to understand - function of the frequencies of the constituent harmonics, called the transfer function. This part therefore was called the time domain. The transfer function was expressed either by a Bode plot (consisting of two related graphs) or by a polar diagram (one diagrammatic representation). The circuits included an inductor (L) here (RLC-circuits).

The cognitive skills needed were calculations, and measurements. The metacognitive skills needed were doing open ended assignments, reasoning, weighing procedures against each other, working methodically. The students had to learn that outcomes of measurements and predictions from calculations had to fit within the accuracy of the measurement ("measurement error"), and they had to explain what they were doing and why (reasoning). The strategy that must be learned, thus was: always compare the results of different methods in empirical investigations. The framework that was used to instruct the students about the strategy contained 34 items, among them five about gathering, interpreting, and focusing information. This framework was identified by asking the responsible teacher and the experience teaching assistants (TA's) what they meant by insight and systematic approach (or working in a methodical way), and how the researcher could measure the relevant variables. For more details about the course, see 3,4
The course was analyzed with respect to high level learning of good, moderate, and weak students. It turned out that the good students (30% of the population) understood the strategy right away from the description. They were not satisfied about their performance in the difficult assignments of the first domain (boosting, see Fig. 1a) and continued to improve after feedback from the TA’s on their first logbook (see Figure 1b). But then, after they reached the level “good” they shifted their attention to understanding the subject matter and their performance on the measurement assignments dropped. This demonstrates non-linear learning because of reallocation of effort and time. The same applies to the moderate students but in a lesser sense. Another important factor is that only 47% of the students performed sufficiently in the first domain. This made them aware that more effort was needed to pass the course.

Several metacognitive skills were measured. It turned out that the moderate students (60% of the population) continued to improve the use of these skills, and approached the level of performance of the good students (see Fig. 2). This in contrast to the weak students (10% of the population) who did not improve these skills at all. The weak students did not show a reallocation of effort as could be seen from the time they used to prepare for the course (Fig. 3). From this figure it will be clear that moderate students put as much effort in preparation as the good students did for session 7, where the

![Image of Figure 1](image)

*Figure 1. The performance in the application of the metacognitive strategy in NA for the three categories of students in the three domains of the course. The means of the scores of good, moderate and weak students on measurement and open-ended assignments in the assessments of the three logbooks are presented. Assessments 1, 2 and 3 relate to the logbooks from the three domains, respectively. Where the weak students differ significantly from the others, this is indicated by a dot.*
Figure 2. The performance in four of the six metacognitive skills for the three categories of students in the three domains of the course (mean scores). Significant differences between mean scores of the good and the moderate students are indicated by two circles. Where the weak students differ significantly from at least one of the other categories, this is indicated by a dot.

Figure 3. The time spent by the students for the preparation of the lab tasks at each session. The first and sixth sessions require no preparation and are omitted from the graph. Where the mean scores of the weak students differ significantly from the others, this is indicated by a dot.
difficult frequency domain started. In the past the students complained at this point that this topic had not yet been treated in the lectures, what still was the case, but complaints were over now.

Another remarkable change was that the students no longer asked the TA’s “Is this measurement result correct, sir?” but instead compared their measurement result with the calculation result, and even detected the influence of the measurement instrument as a source of deviations of the results.

Design of the course

The four metacognitive (MC) variables as implemented in the course are presented in Table 1. Some terms require an explanation. The MC strategies are interventions of the teachers to control learning on a high level. The MC strategy to be learned by the students is the strategic approach that is based on the framework presented as part of the task.

An Advance Organizer represents the basic structure of knowledge in the topic. In the present case it contains the basic electrical circuit (or network) elements, the electrical quantities voltage and current, their orientation, representations in symbols, the structure of a circuit, its representation in schematics and in formulae. These seven chunks of knowledge can be held in working memory at the same time, what makes having an overview of ENA possible. These concepts are at the same time so abstract and general, that they can be explained in terms that the students already know and thus structure their prior knowledge. In this way their knowledge becomes organized and ready for the knowledge to come. No further research has been done on this aspect, however.

Table 1. Educational interventions and effects for metacognitive (MC) objectives

<table>
<thead>
<tr>
<th>MC variants</th>
<th>MC interventions and objectives</th>
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<tbody>
<tr>
<td>MC strategies</td>
<td>Course is divided into three domains (prior, treated, resp. new knowledge)</td>
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<td></td>
<td>Increasingly complex tasks within each domain (homework to open assignments)</td>
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<td></td>
<td>Help on framework fades over domains (learn, practice, apply)</td>
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<td></td>
<td>TA’s are trained on helping to find answers and information</td>
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<td></td>
<td>Students work in pairs (for reciprocal questions, explanations, and discussions)</td>
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<tr>
<td>MC goals/ tasks/</td>
<td>An Advance Organizer provides information on a basic structure of knowledge.</td>
</tr>
<tr>
<td>information</td>
<td>A framework for doing research provides info on a strategic approach that is to be learned, e.g.</td>
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<td></td>
<td>Finding information is the student's own responsibility</td>
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<td></td>
<td>Compare different methods to measure or to calculate</td>
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<td></td>
<td>Construct a “cookbook” for the task</td>
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<td></td>
<td>Compare prediction from calculation and result from measurement</td>
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<td></td>
<td>Individual reports (logbooks) over each domain</td>
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<td></td>
<td>Just in time feedback (before the next domain starts)</td>
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<td>MC experiences</td>
<td>Feeling of difficulty of final level: Boosting (start difficult)</td>
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<td></td>
<td>Feeling of effort needed: Early marking (time and effort allocation if necessary)</td>
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<tr>
<td></td>
<td>Feeling of cognitive conflict or contradiction (circuit vs. schematic, signal vs. oscilloscope picture, linearity of circuit vs. measurement results)</td>
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<tr>
<td>MC knowledge</td>
<td>Know what method is best, easiest, fastest, …</td>
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<td></td>
<td>Know what to study when.</td>
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<td></td>
<td>Have overview, insight. Know abstract theoretical concepts.</td>
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<td>Know how to design empty tables.</td>
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<td>Know the influence of measuring instrument as detected from results.</td>
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</table>
When students work in pairs, they question each other, and explain stuff to each other. This may be considered as reciprocal teaching, a method used by Brown et al. to train metacognitive skills successfully. Also students discuss on matters they do not agree about when working together. The disagreement can be considered as a cognitive conflict, the discussion provides an instrument to rise to a unifying or deciding metacognitive level.

“Boosting” means that the students get the impression that the course is more difficult than in fact is the case. This “illusion” is created by including open ended assignments in the first two parts of the course, while in the last part the most difficult assignments are measurement tasks. In fact the students’ feeling of difficulty (a metacognitive experience) is influenced in order to raise their effort.

Early marking has to be distinguished from “Boosting”. Early marking was done in the entrance test, and in grading each logbook after each of the three domains. Early marking gives the students a real metacognitive impression about the difficulty of the course, not an illusionary one. Early marking may lead to the realisation that the course requires too much effort from some students so that these students may drop out and repeat the course next year.

Cognitive conflicts can not only be raised between students but are also an inevitable part of the subject matter. An example is presented in Fig. 4. Here two equivalent representations of the same electrical circuit are presented. Some students are not able to see the equivalence without extra help. Alternatively, the same schematic of an electrical circuit can be realized into differently structured set-ups. It is supposed that solving this cognitive conflict leads to a metacognitive insight about the difference between a circuit in reality and in representation.

Figure 4. Equivalent representations of an electrical circuit.

One of the reasons that the students can work together but have to report individually lies here: Solving a cognitive conflict can be done in different ways, the insight that comes is not uniform across people. In general this is true for all metacognitive variants: they cannot be observed easily but have to be deducted from reports by the students or from observations. Therefore the students have to report individually in their logbooks about what they did and why during the course in all types of assignments, including homework assignments, preparative assignments (new concepts, new phenomena, new calculations, new measurements), measurements assignments (predict and compare) and open ended assignments.
Two levels of learning

The distinction of two levels of learning is of more importance than in this course only. A description of learning in practice on the two levels is valuable for all education. Therefore research data were added from the three projects in the first year of Electrical Engineering at the University of Twente, where students work in teams of four. Also from lectures, tutoring hours, and other labs that were improved, including the introduction of computer aided learning, partial exams, peer assessment, and co-operation to solve problems. The research method here was an identification of the educational aspects with the aid of the two level and four variants of each level framework by comparison.

First it must be clarified that low level learning contains two components. The first is that the task to be done or skill to be learned is low level. Second that the learning is low level, i.e. teacher-guided. Here it must be stressed again that low level is not a negative characteristic. Ciphering, or typing blindly are low level skills but very important. Learning these skills under the strict guidance of a teacher or under the strict guidance of a computer program that replaces the teacher, are good practices.

High level skills are e.g. to identify, investigate, design, understand, reflect, evaluate, in open ended assignments or tasks, and project work. Improving memory is another example, but using notes to help memory not. Several so-called higher order skills include both high and low level sub-skills, like planning, memorizing and recalling, and solving problems. The low level part has to do with using pen and paper, the high level part with thinking about your own or other people’s skills, knowledge, and feelings. Learning on both low and high level has to be described.

The description will use the term “educational functions” (see Table 2). The educational system is thought to consist of a student and a teacher who gives instructions to the student. The functions of this system can be fulfilled by the teacher, the student, or both. The concept of teacher has to be considered as an abstract concept: his function can be realized via lecture notes, computer aided instruction, or by fellow students. Eight educational functions are distinguished. Motivation is the engine of education and involves both feelings (e.g. liking the exercise or the subject matter) and deliberations (e.g. grasping the usefulness of a skill or of a course). The goal is what should be the outcome of the task, or of learning in case learning sub-tasks are included. The activation of prior knowledge represents the conceptual and other tools the students have to work with in the task.

Orientation means that the students should have an idea how to execute the task, and might include watching a demonstration, reading instructions, and planning the task. The execution of the task is the only function that the students have to fulfill themselves, but the teacher has to see that it happens (sometimes using sticks and carrots). Evaluation means that the outcome of the task should be compared with the goals and the way it was done analyzed with respect to effectiveness and efficiency. Grading is a function that guarantees an output from the teacher-student system to the administrators of the school in order to pass the student onto a next course. Low or high grades, both factual and expected, can influence motivation and planning. Improving is a function that has to do with better execution of the skill in later tasks of the course or in following courses, and might include special learning sub-tasks like elaborating or summarizing.
Table 2. Two levels of learning activities in educational systems (student and teachers)

<table>
<thead>
<tr>
<th>Educational functions</th>
<th>Teacher-guided learning (Superficial level, cognition)</th>
<th>Student-regulated learning (Deep level, metacognition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Follow instructions. Read in lab. Observe demonstrations Get answers from teacher</td>
<td>Compare methods. Prepare at home. Plan and execute a try-out Learn to find answers yourself</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Check results (Is this correct sir?) Continue to the next task</td>
<td>Compare predictions and results Reflect on possible improvement</td>
</tr>
<tr>
<td>Grading</td>
<td>Grading after the course. Final mark only.</td>
<td>Working towards a chosen grade. Early marking</td>
</tr>
<tr>
<td>Improving</td>
<td>Repeat, improve, use, repeat. Automatize. Faster, less errors, less hesitations. Learn what was wrong (after task) Continue with too low effort Do not take risks</td>
<td>Learn, practise, apply. Make flexible, in different domains. Generalise, shorten, in mind. Just in time feedback (fore next task) Relocate resources (effort, time) Balance resources, grade, understanding</td>
</tr>
</tbody>
</table>

A practical description of a course as a sequence of tasks is thus possible. The description in Table 2 of the empirical difference between low level and high level learning is found in a phenomenological way but based on the theoretical concepts cognition and metacognition and their four variants. Where in the formulation pairs of students working together are mentioned one can also read students in larger teams.

It will be clear from Table 2 that what is good practice for low level learning may not be good practice for high level learning, and vice versa. For instance, when the students have to learn to handle a tool, they should execute the prescribed steps individually, but might write a common report about the outcomes. When the students have to learn higher level skills they better work together in planning the work, but report individually about their approaches and insights.

When both low and high level goals are to be served at one time and are not well distinguished, an educational conflict will arise. In the present course the focus was on high level skills, and the low level skills were trained in separate preparatory assignments in each domain. The low level skills were needed in the comparative measurement assignments and in
the open ended assignments, where the high level skills were required. The logbooks were graded with respect to the high level skills as reported by the students.

**Discussion, conclusion, and applications**

There are many ways to design instructions with good effects in practice. And specific design rules can lead to both good and bad practice, depending on the situation. It cannot be proven that specific design rules are the only possible ones for a given course, nor can it be proven that only by specific design rules a good course can be designed. Thus it is not possible to give general, prescriptive design rules for courses. It is however possible to describe educational practice with the aid of various theoretical backgrounds. The approach that was used here comes from activity theory, in which the concept of action plays a central role. “Action” can be considered to be equivalent to “task”, and thus is both a practical and a theoretical concept. Based on this concept the tasks and the learning that comes from tasks were described.

The basic unit of analysis was here instruction-task-product, and the basis educational system the system of student and teacher, in the most general sense. The course was considered as a sequence of tasks. The focus was on cognitive development of the students. It was found that this course had good results for good and moderate students. However, it was not clear why the weak students and some of the moderate students failed. It might be that for these students personal issues played a role (that is priorities or motivation), or lack of personal development.

Not included were important issues like the influence of the school or organization on learning; the influence of social interactions among the students and with the teacher; interactions among the courses like insufficient prior knowledge from earlier courses, or an overloaded curriculum; long term learning (it might be years later that students say that they learned a lot from a course with heavy demands).

Other aspects not included were the changes in the subject matter due to developments in the field of study, and new instruments and tools that become available. Nor the changes in society that make recent student generations different from the old ones, and make tools available to everybody that were not thought of 30 years ago: high speed personal computers with enormous memories, and communication systems that work at high speed, across the world, accurate, and invisible to the teacher when used in class.

It was supposed that these factors were not important in the present outcomes. Research has been done on these points, is going on, and further research has to be done to find out in what cases these factors become important and will have a non-negligible or a desired effect. It is my opinion that the basic structure for cognitive development as presented here will remain valid. Especially the long-term effect of a training like the present one would be necessary to know.

This structure can also be used in a systematic way to find shortcomings in education. The first six educational functions should therefore be checked in reverse order. When the results of a course are all right on both levels, there is no reason to improve it. If this is not the case, one proceeds by evaluating the processes: the execution of tasks, the orientation by the students, the prior knowledge they have, their goals, and their motivation. Motivation is the
last item in this chain, but not the least, because it is the driving force behind everything. Students who are strongly motivated can do a course without any formal instruction by a teacher.

Nevertheless the description makes clear that dissemination of evidence-based educational practice will meet fundamental problems. It can be proven that in any educational system a motivational drive is needed, and that in practice motivational drives can be identified (but sometimes for goals that do not coincide with the teacher's). But what type of motivational drive is best, depends on the students, the teacher, the designer, the topic, the curricular program. The students are not empty bottles that can be filled by evidence-based practices, as computers can.

What is good practice also entirely depends on the context. It depends next to the factors already summed up also on the tools available, the infrastructure, and the amount of money. And last but not least, it depends on what students you want to prepare for what future. At the moment the present is changing so fast that it is an illusion to think that we have time enough to study good practices and based upon this research to improve education. At the time the improvement can be implemented, the content of education has changed. It is my opinion that teachers should improve education themselves, in cooperation with the students, and with the aid of some phenomenological design rules based on some general theoretical concepts.

It has been made clear that good practice involves solutions to conflicting issues. Teachers who want to teach skills at a low level and skills on a high level at one time, are coming into trouble. They either have to solve this educational conflict in practice, or separate the two goals.

What is the value of this conceptual framework? The descriptions are good candidates to be applicable for any learning task and any sequence of learning tasks in which the goal is to learn a strategy based on technical concepts and skills. The present description may be generalizable to tuition hours in which an approach to solve problems in a systematic way is taught. And also to teach understanding, planning, communication, research skills, design skills, etc. provided that a systematic approach for these higher skills can be devised. The generalizability of the descriptions has to be studied.

Ideas to be used in course design based on this framework are
1. Distinguish high level and low level learning goals.
2. Separate tasks for high level and low level learning.
3. Include interventions based on all four (independent) variants of high level and low level functioning: information, experiences, actions (skills), and knowledge.
4. Pay attention to the motivational drives of the students, and look through the eyes of the students to your course.

These are all metacognitive ideas, using abstract educational concepts, and therefore foster generalizability. The present conceptual description of education based on the attention for motivational drives of the students, on distinguishing two levels of learning, combining four variants of functioning on both levels, and a practical approach to sequences of tasks, seems a good candidate to promote dissemination of good practices.
Bibliography
