Excerpt from Edström, K. (2017) *Exploring the dual nature of engineering education: Opportunities and challenges in integrating the academic and professional aspects in the curriculum*, Doctoral thesis in Technology and Learning, KTH. (Please contact kristina@kth.se for a copy of the whole thesis.)

CHAPTER 2. EFFORTS TO INTEGRATE ACADEMIC AND PROFESSIONAL AIMS

The following chapter explores more precisely *the nature of the endeavours* referred to as "engineering education development" in this thesis. The chapter is structured as follows. First, the CDIO initiative is briefly introduced, followed by an exposition of its strategies for integrating the disciplinary theory and professional aims, in curriculum development on the programme and course level, and in faculty development. Along the way, a few mini-cases are presented as illustrations and some of the literature found useful in this endeavour is reviewed.

2.1. Engineering education development – the CDIO approach

2.1.1. Taking the initiative

The CDIO Initiative for engineering education reform started as a project in 2000 by the Massachusetts Institute of Technology (MIT) in the United States, and three Swedish universities: Chalmers, KTH Royal Institute of Technology and Linköping University. The starting point was the recognition that engineering education had become increasingly distanced from engineering practice, as engineering science had replaced engineering practice as the dominant culture among faculty in the past decades (Crawley, 2001). This created a need to "educate students who understand how to Conceive-Design-Implement-Operate (CDIO) complex, value-added engineering systems, within a modern team-based engineering environment". In the original funding application, the partners stated that by embedding hands-on engineering experience, "education will be improved in two ways: it will give students a deep working knowledge of the fundamentals; and it will simultaneously educate the students in the system development process" (MIT, 2000).

Each university chose a pilot programme as project partner: it was the Aeronautics and Astronautics programme at MIT, the Vehicle Engineering programme at KTH, the Mechanical Engineering programme at Chalmers, and the Electrical Engineering and Applied Physics programme at Linköping university. The four partners set out to jointly develop the reform concept methodology, and simultaneously applying it in their respective programmes. Quite soon, other universities showed an interest and were welcomed as collaborators. When the first edition of the book *Rethinking Engineering Education: The CDIO approach* was written (Crawley, Malmqvist, Östlund, & Brodeur, 2007) some twenty institutions had already joined, by the time of the second edition (Crawley, Malmqvist, Östlund, Brodeur, & Edström, 2014) they had reached one hundred, and to date the CDIO Initiative is a worldwide community with over 140 member institutions. See Figure 2.1 for a world map. The CDIO community holds two international meetings per year, one of which is the annual conference. Most regions, colour-coded in Figure 2.1, also organise annual regional meetings. The organisation has evolved with democratic elections of leaders and council members, whereas the ten first members previously held permanent seats. For more details on the history of CDIO see paper IV (Edström, 2018). In the following, the resulting reform concept is described.

Figure 2.1. World map of CDIO collaborators, 2017, made with Google My Maps. Retrieved from www.cdio.org, where a complete list of collaborating institutions can also be found.

The programme-level scope is a key defining feature of CDIO. Since *students experience a programme*, it should not be seen "as a set of elements, but as a system in which each element carries both individual and collective learning objects for the program" (Crawley et al., 2007, p. 17). The CDIO curriculum model can essentially be characterised as programme-centric curriculum development with an outcomes-based approach. In essence, the curriculum theory implied in CDIO specifies a number of logical links, with the programme at the centre. The key characteristic of *the integrated curriculum* is the ideal to integrate the theoretical and the (other) professional aims, in every stage of this system:

- The starting point is to formulate a vision of *what engineers do*.
- What students therefore need to learn is expressed as *intended learning outcomes at the programme level*.
- These are apportioned to the course level, as *course learning objectives*.
- The course learning objectives are finally reflected in the design of *learning activities* and *assessment of student learning outcomes*.
- In the steady state, these links are continuously improved through *cycles of evaluation and development* involving the programme stakeholders.

It is worth noting that today the outcomes-based approach is mainstreamed in large parts of the world, but at the time when the CDIO initiative was started it was quite novel. This was not least true for the Swedish universities. At the time, the US-based Accreditation Board for Engineering and Technology (ABET) had adopted an outcomes-based accreditation scheme from 1997 (ABET, 1994), so the MIT team were ready to share experiences of formulating and using learning objectives. The Swedish partners could contribute to the curriculum model the ideas of constructive alignment (Biggs, 1999), which provided principles for outcomes-based course design. In 2007, when the same paradigm was implemented in Swedish higher education through the Bologna process (Prop. 2004/05:162), the CDIO collaborators had up to six years experience of outcomes-based curriculum development *of their own volition*. At the CDIO member universities there was considerable new expertise, which became sought after by colleagues in other programmes and in other universities. Hence the Bologna implementation could to a larger extent be interpreted as a genuine opportunity for meaningful development, and less as a bureaucratic imposition (cf. Aamodt, Frølich, & Stensaker, 2016; Bleiklie, Frølich, Sweetman, & Henkel, 2017; McGrath & Bolander Laksov, 2014).

The CDIO model for curriculum development is *tightly controlled* through the official documents, mainly the CDIO Syllabus and the CDIO Standards, and at the same time *completely open source*, meaning that one can pick and choose, modify and adapt as desired, even give it a new name. Together with the great diversity among member institutions with their various specific circumstances and needs, this makes implementations considerably different with many “dialects”. What will be presented here is a generic model, as defined by the standards, along with illustrations from implementations at Chalmers and KTH, both technical universities in the Swedish context and original CDIO founders.

The following description is structured along the framework of the CDIO Standards. The main objective is to show the attempts to integrate disciplinary theory and professional aims through curriculum development, first on the programme level, then on course level, and finally in faculty development. Here, it is worth reiterating that *development is a normative activity*; it is directed towards some values. Hence, there can be no such thing such as value-free development. This section will also show the values embedded in the CDIO concept, as well as some of the rhetoric used to promote these values.

2.1.2. Programme level development

CDIO Standards for programme development

Standard 1. The Context Adoption of the principle that product, process, and system lifecycle development and deployment – Conceiving, Designing, Implementing and Operating – are the context for engineering education.
Standard 2. Learning Outcomes Specific, detailed learning outcomes for personal and interpersonal skills, and product, process, and system building skills, as well as disciplinary knowledge, consistent with program goals and validated by program stakeholders.
Standard 3. Integrated Curriculum A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills.
Standard 12. Program Evaluation A system that evaluates programs against these twelve standards, and provides feedback to students, faculty, and other stakeholders for the purposes of continuous improvement.

The starting point for curriculum development is to form a vision for the professional competence of graduates (standard 1) and express it as intended learning outcomes for the programme (standard 2). The dual nature of engineering education is made explicit, by stating that the learning objectives should reflect a deep working knowledge of the fundamentals, as well as the professional competences for technology development and deployment. Standard 2 also specifies the need to engage with programme stakeholders. Per standard 3, the programme level objectives are broken down and assigned to the course level, integrating disciplinary fundamentals with professional engineering skills. The result, *the integrated curriculum*, is often documented by a matrix showing the responsibility of each course towards the programme learning objectives (Malmqvist, Östlund, & Edström, 2006). Standard 12 devises a continuous programme evaluation system, again involving stakeholders.

Programme-led curriculum development – the case of Mechanical Engineering at Chalmers

To illustrate the programme development in CDIO, we turn to the Mechanical Engineering programme at Chalmers, one of the four original project partners. It is a five-year programme, combining a Bachelor and Master of Science in Engineering. Their experiences are documented through a series of publications, not least in CDIO conferences. Though mechanical engineering can be the broadest of fields, the Mechanical Engineering programme has a vision of the work it should prepare students for, namely:

> "to participate in and lead the development and design of industrial products, processes and systems for a sustainable society. The programme also prepares for positions in other areas of the society where skills in analysis and processing of complex open-ended problems are of great importance. During the studies, the student shall be able to develop her/his personal qualities and attitudes that will contribute to professional integrity and to a successful professional life" (Malmqvist, Bankel, Enelund, Gustafsson, & Knutson Wedel, 2010, p. 3)

The curriculum development is documented in the programme description (Malmqvist et al., 2006). Its function is to communicate the current state of the programme and the rationale, and also the next steps. It makes it easier for the programme team to stay focused and prioritise among new ideas and proposed actions, since these will be discussed in terms of their contribution to the goals of the programme (Malmqvist et al., 2010). The programme description documents how ethics, communication and teamwork skills, etc., are integrated in the course learning objectives, according to standard 3.

For this thesis, one of the most interesting developments in the Mechanical Engineering programme has been the integration of computational mathematics, which has strengthened the connection between engineering and mathematics. The rationale was, in short, that students need to learn to solve more general, real-world problems, while they can spend less time "solving oversimplified problems that can be expressed analytically and with solutions that are already known in advance" (Enelund, Larsson, & Malmqvist, 2011). One of the guiding principles was that students should work on the *complete problem*: from setting up a mathematical model and solving it, to simulation of the system, using visualisation to assess the correctness of the model and the solution, and comparison with physical reality. The interventions in the programme involved new basic math courses including a an introduction to programming in Matlab (a technical computing language and environment), new teaching materials (since most textbooks do not take advantage of the development in computing), integration of relevant mathematics topics in fundamental engineering courses (such as mechanics and control theory), and cross-cutting exercises, assignments and team projects shared between the mechanics and strengths of materials courses and mathematics courses. We can note that instead of seeing this as a task for mathematics teachers to solve within the mathematics courses, a *programme-driven approach* was applied, where making connections to mathematics in engineering subjects was at least as important as making connections to engineering in mathematics.

Just as in the previous example, the integration of sustainable development demonstrates how the programme approach enables systematic integration of important topics in several courses, while maintaining links to overall programme learning outcomes and ensuring progression (Enelund, Knutson Wedel, Lundqvist, & Malmqvist, 2013). Programme learning objectives express the sustainability competences in the Mechanical Engineering program, for instance that students should be able to "describe and estimate the economic, societal and environmental consequences of a product or system through its lifecycle". Through the programme, sustainability elements are pervasive and adapted to the context. Course learning objectives show how courses carry partial responsibility in relation to these programme objectives, and in progression through the programme. Students first encounter sustainability in the *Introduction to Mechanical Engineering* (standard 4). It is then integrated into several of the engineering fundamentals courses where it is applicable, e.g. in *Thermodynamics*, *Materials Science*, *Material and Manufacturing Technology*. There are also courses with sustainable development as a main topic, such as *Sustainable Product Development*. Finally, the specialisations on master level also have various degrees of sustainability focus.

A significant aspect of this case is how the education is organised, and here the model developed by the CDIO team in Mechanical Engineering has also had considerable influence across Chalmers. For strategic issues and prioritisations the programme leader is supported by an advisory board, with industry, students, admin and faculty represented. For operational issues, the programme office, with an administrator and a study counsellor, supports the programme leader. Chalmers has a "buyer-seller" model in which the programmes commission courses from the delivering departments. In a yearly cycle, the programme leaders reviews the evaluations for all courses, and negotiates next year's course offering in a dialogue with the vice head of the delivering department. An *agreement* is written to document learning objectives, content, pedagogy and budget of the courses delivered by the department. While the agreement process is a collegial dialogue, in the end the programme controls the budget, approves the course syllabus documents, and is the recipient of course evaluations. As a result, this has enabled the programme team to implement the integrated curriculum, keeping the programme unified while still being a composite of courses from several departments and disciplines. As a result, the curriculum can also be further developed through a relatively agile process. In summary, the Mechanical Engineering programme has systematically created conditions for leading, planning and developing the programme, and for *constantly setting new goals*. It has come out on top of national evaluations, and attracted numerous awards (Malmqvist et al., 2010). Further, this organisational model, with the strong power bases in the programmes, has influenced the education organisation across Chalmers. For the university, it is a mechanism to ensure that the educational resources are spent where they benefit the programmes, as no course is established and offered unless a programme commissions it, and keeps including it in the yearly agreement.

2.1.3. Course level development

CDIO Standards for course design

Standard 7. Integrated Learning Experiences Integrated learning experiences that lead to the acquisition of disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills.
Standard 8. Active Learning Teaching and learning based on active experiential learning methods.
Standard 11. Learning Assessment Assessment of student learning in personal and interpersonal skills, and product, process and system building skills, as well as in disciplinary knowledge.

Standard 7, 8 and 11 constitute a course design model corresponding to constructive alignment: the learning objectives, learning activities, and assessment should be aligned. The integration between disciplinary knowledge and professional skills should apply in all these components. In the integrated curriculum (standard 3) each course accepts responsibility for a portion of the programme objectives regarding some professional competence, in addition to the deep working understanding of fundamentals in the subject. This integration should also be reflected in the way the course is taught (standard 7 and 8), and assessed (standard 11). For instance, in the Mechanical Engineering case above, the planning on programme-level (standard 3) went hand in hand with programme-driven course development, to address the learning objectives that were assigned to courses.

In the following, two cases are presented to illustrate CDIO educational development on course level. The two cases, one a subject course and the other a design project course, were chosen to represent the dual nature of educational development in CDIO, which recognises the *discipline-led* as well as the *problem- or practice-led* components of education. Table 2.1 shows some arguments for why both logics are necessary, and how they can form a productive relationship.

Table 2.1. The need for both discipline-led and problem/practice-led learning. Adapted from (Edström & Kolmos, 2014)

Discipline-led learning is necessary for:	**Problem/practice-led learning is necessary for:**
▪ Creating well-structured knowledge bases ▪ Understanding the relations between evidence/theory, and model/reality ▪ Methods to further the knowledge frontier **…while also connecting with problems and practice:** ▪ Deep working understanding (ability to apply) ▪ Seeing the knowledge through the lens of problems ▪ Interconnecting the disciplines ▪ Integrating skills, e.g. communication and collaboration	▪ Integration and application, synthesis ▪ Open-ended problems, with ambiguity, trade-offs ▪ Problems in context, including human, societal, ethical, economical, legal, etc. aspects ▪ Practicing professional work modes ▪ Design – in Theodore von Kármán's words: "Scientists discover the world that exists; engineers create the world that never was" (NSF, 2013) **…while also connecting with disciplinary knowledge:** ▪ Discovering how disciplinary knowledge is used ▪ Reinforcing disciplinary understanding ▪ Creating a motivational context

These cases illustrate some of the improvements advocated by the CDIO approach, but they are examples and by no means complete. One reason for selecting them is that they share a common theme, which was to represent cost-effective implementations.

Improving student learning in a subject course – a case study

Paper I in this thesis exemplifies CDIO development on the course level, in the context of discipline-led learning. The role of this paper is to indicate how a subject course can improve its contribution to professional preparation while at the same time strengthening students' understanding of the technical fundamentals. Hence, it shows that the ideal of synergy between disciplinary and professional aims can be realised on the course level.

> Edström, K., & Hellström, P.-E. Improving student learning in STEM education: Promoting a deep approach to problem-solving. Manuscript in preparation.

The paper describes and analyses the results of an intervention for improving learning in problem-solving sessions, called student-led exercises. Briefly, the teaching method works as follows: instead of the teacher demonstrating a set of problems on the board (which is considered "normal" or traditional at KTH), students are randomly selected to present their solutions, which they have prepared in advance. The paper describes how this teaching method was implemented at KTH in a course on *Semiconductor Devices* by the second author, Per-Erik Hellström. Further, Carl Henrik Görbitz applied the same method in the very large first-semester *Introduction to Chemistry* at the University of Oslo. The paper presents quantitative data in the form of course results, qualitative data in the form of student interviews made mainly for evaluation purposes, and teacher reflections over the experiences. From a methodological perspective it was valuable to have two contrasting implementations in different contexts (a very large, first-semester course vs. one in the third year with a smaller class), because they could provide different insights regarding the potential advantages of the teaching method. While the results of the *Semiconductor Devices* implementation indicated improved understanding and motivation, the most consequential result in the *Introduction to Chemistry* was a significant decrease in dropouts.

The results demonstrate how even a modest and cost-effective intervention can improve the contribution of subject courses, improving students' understanding of disciplinary theory *while also allowing them to practice communication skills* (Standard 7). The point here is to demonstrate that every ordinary subject course should be able to contribute to the integrated curriculum at least on this very modest level. It also shows how the deliberate integration of relevant skills also generates an active learning format (Standard 8). The activity where students prepare, present, and discuss the solutions is far better aligned with professional practice than an activity where they are mainly copying given solutions, for cramming later. Since the intervention increases student understanding of the subject, and is cost-neutral in terms of teacher time, this is a contribution to professional preparation that every subject course should be able to achieve. In fact, even for an educator who is mainly focused on conveying theoretical understanding, the intervention is justified already by considering the improvement in student understanding, and the practicing of communication skills comes as a bonus.

To classify the quality of intended learning outcomes the Feisel-Schmitz taxonomy (Feisel, 1986) (see paper I for an explanation) has been found useful in CDIO because it makes a clear distinction between problem-solving with or without understanding. Problem-solving *with* understanding, labelled "Solve" in the taxonomy, precisely captures the aim referred to in CDIO as *deeper working knowledge*. Problem-solving without understanding, called "Compute" in the taxonomy, relates to one of the most problematic issues in engineering education: the focus on reproducing given solution procedures for standard types of problems. Therefore, taxonomies that downplay this distinction are unhelpful in the context of engineering education development. In the most widely used taxonomy, by Bloom (1956), the application category is placed, as a whole, on a higher level than understanding. In the revised Bloom's taxonomy (Krathwohl, 2002), the parallelism between understanding and application is better recognised, and the new two-dimensional model can accommodate the distinction, although in a more complicated scheme than Feisel-Schmitz. As an analytic tool the Feisel-Schmitz taxonomy tends to resonate widely with engineering educators, including also those who are most interested in disciplinary accomplishments. Hence, the taxonomy has helped identifying common ground, by highlighting the importance of disciplinary theory for professional practice.

Approaches to learning are used to operationalize the quality of learning processes, given how a deep approach is associated with better learning outcomes than the surface approach (see for instance Marton, Hounsell, & Entwistle, 1984). Most notably this is a conceptual underpinning to constructive alignment (Biggs & Tang, 2011), which implies that learning objectives, learning activities, and assessment should be *aligned to invite a deep approach*, and discourage a surface approach. Extending the classic deep and surface approaches, Case and Marshall (2004) identified the deep and surface *procedural* approaches in relation to problem-solving. In paper I, we proposed an amendment to their model, arguing that the deep procedural approach should not only be treated as an intermediate stage towards a more desirable (conceptual) deep approach. While we agree that problem-solving as a learning activity is a means to reach conceptual understanding, it is not only that; it is also about learning to solve problems. This led us to position problem-solving as an aim in its own right, on the same level as understanding concepts and theory. Again, the intention is to find conceptual common ground, acceptable to those who emphasise disciplinary theory as well as those who emphasise what students can do with their understanding. Finally, if the approaches to learning focus on what students do to learn, based on their intentions, the research on epistemological views (Gainsburg, 2015; Perry, 1998) can further explain this by highlighting their views on knowledge. Gainsburg identifies that students with the more sophisticated views increasingly connect mathematical modelling of course problems with the real problems they represent, and with the nature of problems and processes used in engineering practice.

CDIO Standards for problem- and project-led learning

Standard 4. Introduction to Engineering An introductory course that provides the framework for engineering practice in product, process, and system building, and introduces essential personal and interpersonal skills.
Standard 5. Design-Implement Experiences A curriculum that includes two or more design-implement experiences, including one at a basic level and one at an advanced level.
Standard 6. Engineering Workspaces Engineering workspaces and laboratories that support and encourage hands-on learning of product, process, and system building, disciplinary knowledge, and social learning.

PBL, or problem-based and project-organised learning, is an essential component in the CDIO curriculum model. Here, students can work in the logic of *real problems* (Jonassen, 2014; Jonassen, Strobel, & Lee, 2006). Standard 4 and 5 can be seen as special cases of standard 7, since both describe two kinds of integrated learning experiences. Standard 4 recommends an introduction to engineering early in the programme, to give students a first contact with engineering practice and the role of engineers. Standard 5 implies a sequence of design–implement experiences, with progression across the curriculum. By design-implement experiences are meant projects in which the students learn through the development and deployment of products, processes or systems, under working modes that resemble engineering practice. A key feature is to take solutions to a testable state, allowing students to evaluate and reflect on their work, with regards to the process and the results. Standard 6 is about creating a learning environment to accommodate such realistic engineering experiences.

It is a cornerstone of the CDIO philosophy that the hands-on component should run continuously across the curriculum, starting early and progressing through the programme. This can be seen as a reaction to curricula where the first years are filled with basic theoretical subjects, where students risk losing sight of why they wanted to become engineers in the first place (see for instance Holmegaard, Madsen, & Ulriksen, 2016; Holmegaard, Ulriksen, & Madsen, 2010).

Improving student learning in a project course – a case study

The following case is based on the experiences in a master level design project course taught by Jakob Kuttenkeuler and Stefan Hallström, from the Vehicle Engineering department at KTH, one of the original founding partners of CDIO. The teachers have involved me in discussing and designing improvements to the teaching and assessment on a regular basis since 2001, and our joint reflections and experiences have been reported (Edström, El Gaidi, Hallström, & Kuttenkeuler, 2005; Edström, Hallström, & Kuttenkeuler, 2011; Hallström, Kuttenkeuler, & Edström, 2007) and in a book chapter (Hallström, Kuttenkeuler, Niewoehner, & Young, 2014).

It is not the intention here to explain project courses generally, but to describe the course and experiences sufficiently for illustrating two points:

- The *learning perspective* – The case shows a learning-centred design of teaching and assessment. In short, the purpose is not that the students should build things; it is that they should *learn* from building things.
- The *teaching perspective* – The case shows some principles for making this learning activity sustainable from a teaching perspective, as project-based learning is often assumed to be expensive and require high teaching effort.

The course mixes students from several programmes, and its name is *Naval Design* or *Lightweight Design* depending on which programme a student comes from. The scope is 20 ECTS credits spread over an entire academic year, i.e. allocating one third of students' time. Students are divided into large groups, typically of 8-15 students, and given an open-ended task to design, manufacture and test a technical system, typically an unorthodox vehicle. Previous groups have built things like a solar powered aircraft, an autonomous underwater glider, a craft that can plane on the surface but also submerge, an electric single-hydrofoil vehicle for play, and a human-powered submarine (for video clips, see Kuttenkeuler, 2017). While the technical challenge is new for every group, the learning objectives are the same every year. See Table 2.2.

The course design and teaching philosophy is guided by some key principles. The first principle is that *students are directly exposed to real problems* in the project work. In other words, teachers do not stand between the students and the problems. Most previous courses follow the cognitive structure of a subject, where textbook problems are used to illustrate theory, and where the teacher knows the right answers in advance. There, it is often clear from the course context what sort of problem it is and what theory should be used. In contrast, the problems that emerge in the project work come without any labels telling students what theory is relevant. Some problems may require students to search for and use theory and methods that are new to them.

Table 2.2. Intended learning outcomes of the Naval/Lightweight Design course.

Students should be able to:	**Examples of related challenges:**
▪ take on technical problems in a systems view	Knowing and prioritising the crucial challenges and keys to success. Where to start. Considering the implications of different concepts (solutions). Handling the interfaces between sub-systems.
▪ handle technical problems which are incompletely stated and subject to multiple constraints	How to handle interdependent tasks, e.g. idling while just waiting for data from each other. How can the work be assigned to individuals but the big picture maintained?
▪ develop strategies for systematic choice and use of available engineering methods and tools	Knowing what aspects matter most, and keeping focus on them. Choosing the right level of precision, e.g. start by sketching on napkins rather than using supercomputers.
▪ make estimations and appreciate their value and limitations	Using estimations correctly, revisiting and challenging them. Interpreting results in the light of assumptions.
▪ make decisions based on acquired knowledge	Creating a relevant basis for decisions. Act when the information is good enough. Documentation and traceability.
▪ pursue own ideas and realise them practically	Discussing, arguing, debating, standing up for your standpoint, and letting go of darlings. Struggling with real world conditions, e.g. there is no infinitely strong glue.
▪ assess quality of own work and work by others	Reflecting on different approaches. Seeing where one's work made a difference. Reflecting on what can be improved. Role modelling.
▪ work in a true project setting that effectively utilises available resources	Decision-making. Minimising idling. Identifying time-critical tasks. Professionalism.
▪ explain mechanisms behind progress and difficulties in such a setting	How to interpret and handle problems. Getting true status overviews and responding appropriately.
▪ communicate engineering – orally, in writing and graphically	Using all possible modes of communication in authentic situations.

The course design and teaching philosophy is guided by some key principles. The first principle is that *students are directly exposed to real problems* in the project work. In other words, teachers do not stand between the students and the problems. Most previous courses follow the cognitive structure of a subject, where textbook problems are used to illustrate theory, and where the teacher knows the right answers in advance. There, it is often clear from the course context what sort of problem it is and what theory should be used. In contrast, the problems that emerge in the project work come without any labels telling students what theory is relevant. Some problems may require students to search for and use theory and methods that are new to them. At the same time, it can be troublesome for the students to recognise even the most fundamental theory in the wild, such as *Newton's Second Law*, *Ohm's Law*, or *Archimedes' Principle*. As students need to learn how to handle unforeseen and poorly defined problems, the teachers avoid stepping in too hastily to "help" with "correct" interpretations. Further, since the problems are open-ended and in no way prepared or adjusted, there are no black-or-white right answers. Instead of using the teachers for convenient affirmation that answers and solutions are "right", students need to seek different forms of validation and develop their own judgement. In other words, students need to think for themselves, and this can only happen to the extent that the teachers can resist accommodating student expectations, i.e. the desire to get right answers or to avoid the stage of bewilderment. Until students get accustomed to this new order of things, their conceptions of student and teacher roles are often challenged, and so are their epistemological views. There is a tension here, between learning and task achievement. Naturally, if the teacher were constantly "helping" the students, they could build a better boat. Instead, they are allowed to face these highly relevant challenges, because learning is more important (Edström et al., 2005).

In order to prioritise learning, the student teams also need to take full responsibility and ownership. This principle is that the *students own the project,* all aspects of it. If teachers were to start taking initiatives, it could shift students to a more passive role. A major implication is that the teachers' role is to coach and advise in the engineering process, but not to drive it, and *never suggest solutions*. Hence, students are not protected from mistakes, contradictions or confusion. As a result of this principle, the project results will reflect the proficiency of the students, not of the teachers. Again, learning is prioritised over the product performance. A related principle is that *the project sets the logic*, not the teachers. This means that teachers refrain from unnecessarily making decisions in the project. E.g. deadlines are not set by teachers, but by the project plan created by the student team. Teachers do not specify the length of a report; it is inferred by what it needs to achieve in the project. For instance, when the project commissions an investigation by a sub-team, their report should contain precisely the information needed to make the subsequent decision – and the length, and the deadline, follow as *consequences of its function*. For many students this is the first time they write a document that actually has a function; previously they have mostly written to demonstrate to teachers that they deserve a grade, so their normal mind-set is: "What does the teacher want?" When they let go of the teacher orientation, and start to become project-oriented, their work becomes much more meaningful, and easier. Obviously, when teachers refrain from managing (and micro managing) the project, it also makes the course far more sustainable in terms of teacher time.

The assessment system is also designed to generate learning. We note that it is common in project courses to grade group products (or final reports). In our opinion, product grades are loosely related to learning outcomes, and they create disincentives for learning, because when students focus on task achievement they tend to share the task so each of them can do what they already do best. Group grades are also aggregated to hide individual attainment – which is inherently unfair and often creates conflicts due to different levels of ambition. In this course, instead, teachers grade students *individually based on the learning outcomes* as evidenced in the process. Since students work on many different tasks, the principle is that the *students take responsibility for their own learning outcomes*, individually. Furthermore, we believe that doing is not sufficient for learning; students need to reflect in order to turn experience into learning. A portfolio assessment system (for details, see Edström et al., 2005) is designed to generate reflection in relation to the learning goals. For a mid-course formative peer feedback round, each student submits a one-page self-evaluation, which is distributed to all members of the team. It is based on the portfolio and structured according to the learning objectives, with any claims substantiated by referencing project documents that are openly available on the project website. Writing feedback to up to 14 teammates is a comprehensive task, but it is justified by the reflection it elicits. The mid-course feedback comes when students still have another semester ahead of them to make adjustments. For instance, students may discover that they need to engage in different tasks in order to reach all the learning objectives. At the end of the course, after a second peer feedback round, grades are set, individually and in relation to the learning objectives, by the two teachers. Each teacher notes preliminary grades independently, based on a holistic assessment of the portfolios and the work referenced, the feedback given and received, as well as continuous observations throughout the course. They then meet to compare and discuss until reaching consensus. From a teaching perspective, the assessment takes no more time than in other (so called normal) courses. The portfolio model reverses the burden of proof; it is up to the students to show evidence of their individual learning. Furthermore, teachers do not take it upon themselves to provide written feedback; when the students give (formative) feedback to each other, they learn from both the act of giving and of receiving.

The experiences in these two cases, in Hellström's subject course and in Hallström's and Kuttenkeuler's project course, clearly showed new demands on the teacher competence, regarding what to teach, and how to design the learning activities and learning assessment. Next, we turn to the matter of faculty development.

2.1.4. Faculty development

CDIO Standards for faculty development

Standard 9. Enhancement of Faculty Competence Actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills.
Standard 10. Enhancement of Faculty Teaching Competence Actions that enhance faculty competence in providing integrated learning experiences, in using active experiential learning methods, and in assessing student learning.

Standard 9 and 10 both concern enhancement of faculty competence. These are also the standards that are the least discussed, and for which the least progress has been reported by CDIO implementers (Malmqvist, Hugo, & Kjellberg, 2015). The term "enhancement" has often been taken synonymously with activities supporting the further development of the existing faculty, but it may just as well refer to the composition of the faculty, for instance through hiring and promotion criteria (Theodorsdottir, Saemundsdottir, Malmqvist, Turenne, & Rouvrais, 2013). One general challenge with recommending faculty development as part of a programme-centred development concept is that although it is an important condition for success – in fact often the most critical – it is often a domain in which the programme has little influence. This was the case at Chalmers, for instance, where the programme buys courses from departments, but has no (formal) influence on processes ensuring teacher competence, such as hiring and promotion (Malmqvist et al., 2010). Even in systems where a department owns a programme, faculty recruitment and development may prioritise the needs of research over those of education. Cautious steps are taken in many places to strengthen faculty engineering competence and teaching competence. Such policies are most often university-wide. At MIT, a limited number of *Professors of the Practice* can be hired (de Weck, 2004; MIT, 2017). In every hiring and promotion case at Chalmers, at least one of the external evaluators is a teaching expert focusing on the teaching competence of the candidate. In addition, the Chalmers appointment regulations specify special positions based on professional skills, as well as positions up to Professor (not holding a chair) with emphasis on pedagogical expertise (Chalmers, 2013).

Though CDIO Standard 9 is simply named enhancement of "faculty competence", it really refers to faculty *professional engineering* competence, expressed as their "personal and interpersonal skills, and product, process, and system building skills", which are best developed "in contexts of professional engineering practice". Examples of actions to support faculty engineering competence are: sabbaticals to work in industry (including the public sector), partnerships with industry in research and education projects, valuing engineering practice as a merit in hiring and promotion, allowing and encouraging consultancy work, and professional development activities at the university (Malmqvist, Gunnarsson, & Vigild, 2008). It can be noted that the theoretical and scientific competence of faculty is not even mentioned; this is taken for granted, perhaps reflecting the prevailing academic culture of the research-intensive universities where the CDIO approach was first developed.

CDIO Standard 10 concerns enhancement of faculty teaching competence. In the Swedish context, most universities offer courses on teaching and learning to faculty. One reason is that ten weeks of such training was for many years a national eligibility requirement for senior lecturers and professors (Lindberg-Sand et al., 2005). At KTH, the faculty development activity created an opportunity for mainstreaming the CDIO approach to course and programme development. One of the faculty development courses, *Teaching and Learning in Higher Education*, 7,5 ECTS credits (i.e. half the requirement), was redesigned in 2004 to emphasise matters of course design, inspired by the experiences with CDIO. Some 700 participants took the course during the decade when it was offered. One teaching strategy applied in this course was to engage other faculty members as guest teachers, presenting their own experiences of course development. Those cases were analysed as examples, to derive theoretical principles for guiding practical implementation. The presence of the guest teachers also demonstrated locally developed proofs-of-concept, showing that *it works here*. The most prominent cases were the cases discussed above, the design project course presented by Jakob Kuttenkeuler and Stefan Hallström, and the student-led exercises (featuring in paper I), presented by Per-Erik Hellström. The cases in this chapter can therefore also to some extent serve as illustrations of standard 10.

An increasing emphasis on scholarship in CDIO conferences (discussed in the next chapter) could also be seen as a dimension of faculty development, by generating more systematic and scholarly reflection and documentation.

2.2. Further development of the CDIO concept and community

The previous section discussed the development of the CDIO approach (Crawley et al., 2007; Crawley et al., 2014), and showed its strategies for integrating disciplinary and professional learning through curriculum development, and faculty development. CDIO was chosen not because it is the only model available, but because it is representative of an effort to address the tension that is the theme here, and part of the professional engagement that is the background. The rest of this chapter will discuss two engagements to further develop the approach and the community. First, CDIO will be compared with PBL, another educational development concept with a large international community that also addresses the tension between professional and disciplinary aspects. Finally we discuss a present proposal to connect the CDIO community and the field of engineering education research.

2.2.1. Comparing CDIO and PBL

In paper II, CDIO is compared with PBL (problem-based/project-organised learning). Both are models for reforming engineering education with organised international communities. This study came about because both authors, rooted in the PBL and CDIO communities respectively, had often been asked, "Should we do PBL or CDIO?" We felt the need to produce a thorough answer with a systematic approach. The resulting publication was:

> Edström, K. & Kolmos, A. (2014). PBL and CDIO: complementary models for engineering education development. *European Journal of Engineering Education*, 39(5), 539-555.

In this study, the main methodological challenge was to generate a framework for the analysis, and this was done in stages through an inductive, participatory, and iterative approach. The project started by generating a gross list of aspects that could be compared. In three conference workshops, with a total of 70 experienced practitioners as participants, our first iterations of comparisons were presented and discussed. During the workshops some aspects emerged as most salient and productive in generating insights, by revealing similarities, differences, surprises, misconceptions, or unreflected assumptions. The final framework consisted of the following core aspects: history, community, definition, curriculum design, relation to disciplines, engineering projects, and change strategy. Through a correspondence between the authors, complemented with document studies, these aspects were then examined and analysed for PBL and CDIO, respectively, then contrasted. See Table 2.3.

Table 2.3. Summary of the PBL and CDIO comparison (Edström & Kolmos, 2014).

	PBL	**CDIO**
Starting point	The starting point is the learning process. Started in reform universities in the 1960s and 1970s, in response to critical student movements. Applicable in medicine, engineering, science and many other fields.	The starting point is a vision of graduates' competence expressed as learning outcomes. Started at MIT in the late 1990s, forming a project with three Swedish universities, in response to distancing of engineering education from engineering practice.
Communities	Implementation of PBL cannot be estimated, due to different levels of implementation from a single course to whole universities. Several international networks: PBL Global Network, International PBL Symposium, Pan-American Network for PBL.	About 140 institutions are formally CDIO collaborators in the CDIO Initiative. Extent of CDIO implementation is difficult to estimate.
Definitions	A broad educational approach, focusing on the learning process, and loosely defined. The principles can be applied on course, programme, or institutional level, in different fields of education, and any level from school to university. Practices vary, with the McMaster/ Maastricht and Aalborg models well documented.	The CDIO Syllabus addresses what students learn. The CDIO Standards address strategies for curriculum and faculty development. Practices vary among implementing institutions.
Curriculum design	Projects are the platform for student learning.	The 12 CDIO Standards describe an outcomes-based approach for designing the integrated curriculum.
Relation to disciplines	Many hybrid models where at least half the curriculum is subject-based.	Subject courses a major part of the curriculum as integrated learning experiences: students should master a deeper working knowledge of technical fundamentals and simultaneously develop professionally relevant skills.
Projects	Discipline projects, students apply theory to problems in order to reach mainly disciplinary learning outcomes. Problem projects, where students address real problems with contextual and societal dimensions; here the problem determines what theory is used.	Project-based learning features most notably in a sequence of engineering projects, design-implement experiences, where students conceive, design, implement and operate products, processes and systems. Progression through the programme. The intention is not to replace subject courses as the primary site to systematically learn disciplinary knowledge.
Change strategies	Research evidence to show the positive effects of PBL. Well-documented institution-wide implementations. A change management perspective to handle resistance.	CDIO has its origin in engineering, and is created by engineering faculty. Curriculum development as engineering design. Working within the discipline-based structures. Stakeholder involvement.
Relation to research	Centres with researchers specialising in PBL evidence. Much literature documenting PBL, including dozens of books. Two specialised journals: *Interdisciplinary Journal of Problem-Based Learning* and *Journal of PBL in Higher Education*. 807 documents in Scopus (PBL AND "engineering education")	Some literature documenting CDIO, including a few books, journal articles. Peer review in the annual conference from 2009, and a research track from 2016. One special issue forthcoming in *European Journal of Engineering Education*. 278 documents in Scopus (CDIO AND "engineering education")

Both communities have important roles as centres for jointly developing, sharing and qualifying a knowledge base, consisting of the approaches in themselves, as well as the collective experiences in applying them. The knowledge base and the communities serve to strengthen local change agents, who are otherwise often isolated with only their own developed strategies, specific experiences, and limited opportunities for critical reflection. Hence, the communities contribute to the identities of practitioners, and helps legitimise their work. This paper also identified some significant differences in how each community conceptualises and handles the relationship between disciplinary fundamentals and professional aspects. Significant differences were seen in the starting point, the proposed role of disciplines, and the scope of the concepts. In PBL the starting point is the learning process, in that a problem- and project-based approach is advocated, for any type of learning outcomes. PBL is implemented in single courses, whole programmes, or whole universities. It is the PBL format in itself that prepares students for professional practice, through its similarity to working life. Despite the fact that some half of the curriculum in PBL universities is discipline-based, this is less addressed. In CDIO the starting point is to align the learning outcomes with professional practice. This led to the ideal of including both discipline-led and problem/project-led approaches in the curriculum, and there are strategies for both developing the contributions of both types of courses.

After the comparative paper (Edström & Kolmos, 2014) was published, our joint reflections on the differences between the communities continued. In retrospect, it struck us as remarkable that one potential point of comparison was absent. Although the *role of research* is clearly a key difference between the two communities, it did not emerge as a separate category from our process of generating the comparative framework. One reason might be that the categories were generated in CDIO and SEFI conferences, but not in a pure PBL conference where research is more emphasised. The difference was however still visible in the results of the study, for instance when comparing the communities and change strategies. This lack of connection between CDIO and the emerging engineering education research (EER) community became a lasting conundrum, and the source of a new engagement.

2.2.2. Connecting CDIO and engineering education research

Although much work in CDIO had been documented and published, also in international peer-reviewed journals, it was still seen exclusively as a community for educational development. Why the community has not been engaging more in the emerging engineering education research community was therefore truly puzzling. It was even stated already in the original application to the Wallenberg foundation that "a research program on teaching and learning is embedded in our initiative" (MIT, 2000). This led to a new engagement to organise an arena for educational research within the CDIO community, more specifically by establishing a research track starting in the annual conference in 2016. In opening for engineering education research, the hope is to further improve the knowledge base of the work, and strengthen the legitimacy of practitioners, but there are also risks of losing important values. Therefore it felt important to transparently discuss the rationale for this move, and this became the theme for paper III:

> Edström, K. In press, 2017. The role of CDIO in engineering education research: Combining usefulness and scholarliness. *European Journal of Engineering Education*.

The objective of this study was to consider the relationship between engineering education development and engineering education research, from the perspective of the CDIO community. It traces the development of engineering education research (EER) and some of the debates that are relevant for the formation of the field. The narrative is informed by observations during several years in various research and development communities, so here it mattered to be an insider. The development of the EER field, limited to the US and Europe, is distilled to a very short summary presented with support from a number of sources, in particular the key journals involved. It discusses the nature of research that might be most relevant for engineering education development and for furthering the community, by highlighting and comparing three concepts related to different aims of research: Boyer's four scholarships (Boyer, 1990), Mode 1 and 2 (Gibbons et al., 1994), and Pasteur's Quadrant (Brooks, 1967; Stokes, 1997). The aim was to provide perspectives to help make sense of the available opportunities in EER, and discuss implications. In particular, Pasteur's quadrant appeared useful to keep the hopes up that the research mission need not thwart ambitions to improve engineering education. See Figure 2.2.

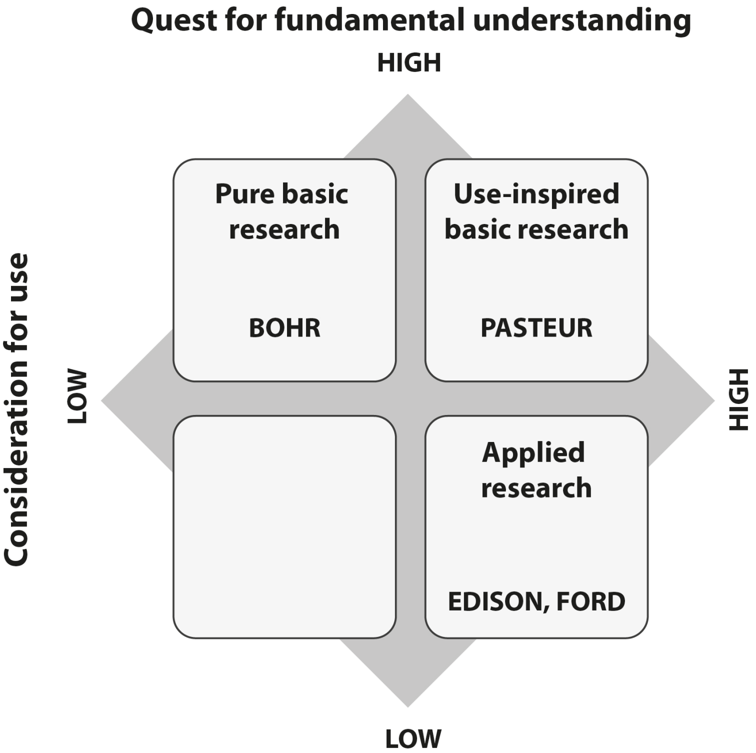

Figure 2.2. Pasteur's Quadrant (based on Brooks 1967; Söderberg 1967; Stokes 1997), from paper III (Edström, 2017).

The ensuing proposal for review criteria in the CDIO conference research track was intended to take a stance in the debates by combining considerations for scholarliness and usefulness. In the 12th International CDIO Conference, held in Turku 2016, the new research track attracted 40 proposals. After the peer review process, 14 full papers were published in this track (Björkqvist et al., 2016). The following year, 40 proposals were submitted for the 13th International CDIO Conference held in Calgary, finally resulting in 11 full papers (Brennan et al., 2017). Further, a special issue on the theme "*Scholarly Development of Engineering Education – the CDIO approach*" was announced in the European Journal of Engineering Education (2016), with contributions currently in the review process. It is an issue for future research to evaluate the results of this move, whether it will actually provide new understandings that are scholarly or useful, or both, or neither, and what other consequences it may bring about.

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This chapter described the CDIO approach for engineering education development. CDIO was chosen, not because it is the only model available, but to represent what is meant in this thesis by “engineering education development”. The chapter laid out, in some detail, the attempted strategies to integrate disciplinary knowledge and professional aspects in the curriculum, on the programme and course level, and in faculty development. Then, some engagements to increase self-reflection and support the further development of the CDIO approach and community were discussed. The first was a comparison of CDIO and PBL, and the second was a subsequent effort to connect the CDIO community with the emerging engineering education research community.

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