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# How to Solve it ?

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This paper describes the redesign of a heat transfer course in the 2nd year BSc. curriculum in Mechanical Engineering in the faculty of Engineering Technology of the University of Twente. The objective was to improve the engineering ability of students to model and solve practically relevant problems systematically, obtain realistic answers, and obtain better scores at regular exams consisting of such type of problem exercises, as well as achieve a deeper learning. The redesign involves reintroduction of systematic problem analysis, enhancement of student engagement towards active learning, aspects of Student Driven/Student Centered Learning, Students As Partners, Decoding the Discipline, and Threshold Learning Concepts. The redesign has resulted in a new learning experience for students and teacher, reflected in increased participation, and positive evaluation results. The percentage of students passing the exam is improved over previous years which may partly be attributed to the redesign and new learning environment created. These positive results stimulated further development.

## 1 Introduction

Engineers solve problems. Engineers "make things work (again)". Engineers seem to have a particular way of approaching "problems" such that in the end a practical solution appears or a realistic answer to a practical question, with a validity either for the time being, or a structural solution to the problem with long term reliability. So in addition to solving a problem they even seem to be able to implicitly predict how long a solution will work or what needs to be done to



Figure 1: Today's learner in transformation to engineer for a resilient society

prevent the problem from reappearing (maintenance). What is the secret of the engineering approach? Is it so really so systematic and organized as it engineers would like us to believe? How much in the approach is "analysis" and how much is "use of previous experience", or "analogy"? What are the "tools" engineers take to the job that we can all recognize, and which concepts are central to mastery of engineering which may be unnoticed by non-experts? Engineers obviously use a mix of knowledge of various disciplines in science, of existing technology, are often driven by a strong curiosity as to "how things work" and possess good technical calculational and analytical skills, to bring an idea of a solution from concept or equations to actual application. The approach is by definition interdisciplinary. The Japanese term "budo" translated as "martial way" or "way of the warrior" used in martial arts (karate, etc)

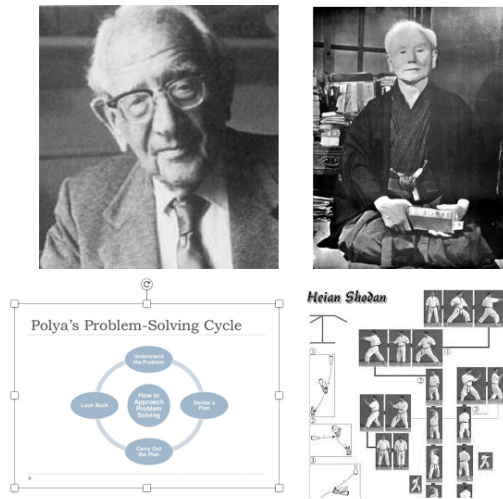
indicates a "way of life" which significantly determines the ways in which learning the art is realized by teacher and pupil, or senior and junior ([1, 2, 3, 4]) Is there an equivalent "way of the engineer" or "way of problem f" ? The "secrets" of martial arts were unveiled by some "masters" dedicated to passing on the techniques, the methods, and the intrinsic values (for life). Funakoshi ([3]) was one these masters owing to his effort and his systematic approach to learning the way of karate it is practiced in many countries in the world nowadays. A systematic way to problem solving was introduced by the pioneering researcher/teacher mathematician Polya [5] who spent much effort motivating students and teachers with this systematic analysis, and can nowadays still be seen in action [6]. Both very motivated and innovative teachers in their field and time are brought together in Figure 2.

The way of problem solving is of course not unique to engineers but general for professionals in Science, Technology, Engineering, and Mathematics (STEM) and "teaching" young students how to solve problems has always been, and still is a major challenge in STEM education, and the topic of many studies. In view of the urgent need to develop new technologies to aid the transition towards a resilient society with sustainable energy resources, minimum use of materials, and minimum impact on environment and on our precious planet education of innovative engineers is more important than ever. In the process of the engineering education students must develop the basic qualities of engineers, problem analysis and problem solving, good understanding of the relevant physics and mathematics, skillful and creative in using the physical and mathematical knowledge to come to realistic answers, and good ability to reflect on results. However, primary and secondary school teaching (methods) have changed as a result of which students enter institutes of higher learning with a different level (or type) of skills than expected by the current generation of engineers. Also, our young generation grows up in a society with constant access to much more, but not necessarily reliable and validated, information that is only a mouseclick (or smart phone swipe) away. This abundance of information makes it difficult for students to get an overview of a topic/field, and see what is really important and what may be effects of secondary importance, whereas it is exactly the ability to distinguish dominant and secondary effects which is crucial in engineering as it may make the difference between being able to solve a problem quickly or not at all. In addition there is a constant pressure of communication via different sources which immediate effect of reduction of the concentration span on a particular task, i.e. studying text or making or practicing exercises, see Figure 1. In [7] undergraduate students use of laptops during a lecture-style class with substantial problem solving activities and graphic-based content was monitored observing they engage in substantial multitasking behaviour and have non course related

software applications open and active about 42 % of the time, which will have a profound negative effect on the learning task. Even more so as students themselves underestimated the time they spent in these applications and they may not fully understand the potential negative impact. In a particular study presented in [8] it was found that students induced to use computers in class perform worse and students who are influenced not to use computers perform significantly better. The negative effects of computer use were found to be concentrated among males and low-performing students and more prominent in quantitative courses. The best role of the digital media in education is thus clearly still open to debate. Finally, students who use longhand to make lecture notes may acquire a deeper understanding of the material than students typing notes on a laptop [9]. This is not only related to laptop distractions but " because longhand notes contain students' own words and handwriting, they may serve as more effective memory cues by recreating the context as well as content from the original learning lesson." In fact, from a study on pre-literate children it is known that brain activation during letter perception is influenced in different ways by previous handwriting of letters verses typing of these letters [10].

Teachers in STEM face the challenge to bring this new generation students from the high school level to the practical engineering level where it is very important to focus on a task, have the practical skills to actually obtain correct results, e.g. not just being able to *find* digitized descriptions of how to do it, but to have actually hands on capability of doing it themselves. The classic approach of lectures and teacher centered classes does not seem to work. In response one argues that it is the level of students that is the problem and pre-college education is different but blaming primary and secondary school (teachers) for the deficits in STEM learning at the University level is not helpful, and in [11] the authors argue that at the institutes of higher learning the education in BSc. programs is often far worse than it could be. They advocate changes across the entire institutes from board to teacher. Faculty must aim to create learning environments in which students are participants rather than passive note-takers or followers. Indeed, it is the role of teacher and learner in the educational process that highly determines its success. It is interesting to note that in the Japanese tradition of martial arts teaching [3, 4, 12, 13] both teacher and learner share the responsibility (towards each other) equally and are both aware of this fact.

In his systematic approach to problem solving Polya distinguishes several phases among which the phase to understand the problem and to see the path to the solution are the most important. In the Netherlands SLO developed the "Systematische Probleemaanpak", and at the University of Twente in the various engineering programs Systematic Problem analysis was a dominant topic [14, 15], with the systematic approach formally



**Figure 2:** Two pioneers and masters of teaching in their disciplines: György Polyá and his way of systematic problem solving (left) and Gichin Funakoshi and his way of the empty hand (karate) teaching.

justified by educational theory (see Section 2.2) and references in the papers.

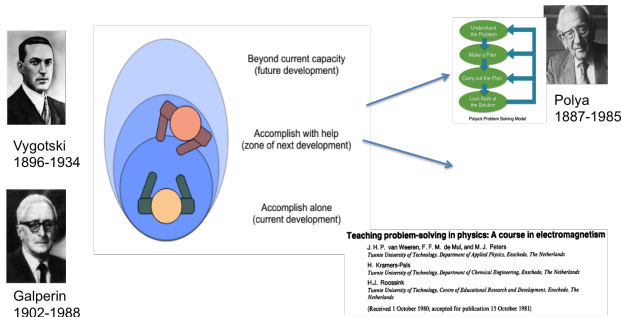
In the past decades the educational landscape in STEM has changed quite drastically inspired by different motives ranging from insights obtained from studies in the science of teaching, the drive of institutes based on funding to increase economic efficiency of education, i.e. by making students pass more efficiently through programs, to the genuine desire to improve the depth of learning and the learning environment. Science of teaching is a very active area of research. Many new concepts have been introduced such as Student Centered Learning, Project Based Learning (PBL) [16] and Student Driven Learning (SDL or SDrL) (see [17] for a short overview). Project Based learning advocates that students acquire deeper knowledge by active exploration of real-world challenges and problems. PBL can be seen as originating in the work of Dewey ([18, 19]). It is a style of active learning [20, 21, 22]. Other developments are Student As Partner [23], Decoding the Discipline [24, 25, 26] and Flipping the Classroom. Many of the new concepts aim to improve the learning process by emphasizing a different part of the role of teacher and learner, and of the class sessions, in the educational process. An essential part in most approaches is that learners are part of an active mutual process, rather than being audience for a teacher, and they learn by “doing and trying” which is an essential part of internalizing what is learned in the constructivism approach (see Section 2.2). Relating back to the systematic teaching in martial arts mentioned above, learning by doing, preferably many times, without a lot of explanation is exactly how martial arts teaching is organized [3, 12, 13]) and leads to increasingly better executed, effective, and efficient techniques and physically understanding of the motion and impact.

However, in spite of all developments it should be

noted that the effectiveness of these approaches and the need for change are subject of strong opinions. Waldrop [20] states about active problem solving that “at this point it is unethical to teach any other way”, whereas Kirschner et al state about Problem based learning and constructivist learning that “based on our current knowledge of human cognitive architecture, minimally guided instruction is likely to be ineffective” [27]

Nevertheless, at many institutes the role of classical lectures is questioned and in the near future likely to decrease. At the University of Twente the Twente Education Model (TEM) [28, 29, 30, 31] was introduced in 2013 simultaneously for the all BSc. programs. The main drivers were innovation and improvement of education towards enhancing the learning environment to Learner-Centered Teaching, as well as budget driven in response to Dutch government guidelines regarding study yields. Project Based Learning has a prominent role. The BSc. program Mechanical Engineering consists of 12 Modules which each focus on a specific theme, consisting of courses and a project. Module 07 of the Mechanical Engineering BSc. program focusses on fluid mechanics and heat transfer.

The module is directed at learning the physical mechanics and fundamental laws related to fluid motion and heat transfer, and the methods derived from it which are used in practice to answer numerous questions in engineering applications such as the forces by flow on structures, or the required rate of heat transfer needed to cool or heat an object or system. The Module consists of 2 courses and a project. The courses are Fluid Mechanics which focusses on the derivation of the conservation laws, flow regimes, flow fields, and determination of forces exerted by a flow for use in design. The second course is focusses on heat transfer, particularly the mechanisms conduction, convection and radiation. The courses are evaluated by regular exams consisting of solving model problems related to practical applications. The teaching form is classic lectures, supported by working classes in which students practice to solve exercise problems. The module is subject to student evaluation every year. In spite of appreciation of the module regarding the relevance of the topic for the ME education, the good organization and the clear interaction between courses and project, the passing grade of the courses is rather moderate. Insufficient problem solving skills and experience is one of the possible causes. In this paper it is described why and how (part of) the Heat Transfer course was re-designed (re)introducing systematic problem analysis, using concepts from the aforementioned innovations in STEM education, and changing the learning environment from classic teacher centered towards student driven learning with various forms of active learning.



**Figure 3:** From Vygotsky, zone of Proximal Development (ZPD) to Systematic problem solving (4 step approach Polya [5] and SPA/SAP [14, 15].

## 2 Educational Context

The university of Twente (before 1982 Twente University of Technology (THT)) is an entrepreneurial university with an active teaching research and innovation culture, supported by the Centre of Expertise in Learning and Teaching (as part of the Centre of Educational Support). CELT provides educational consultancy and support at various levels, as well as the development of professionalisation of teaching, such as courses for Basic Qualification Education, Senior Qualification Education, development of course materials, and support in educational (research) projects, and accreditation. The present work was carried out as project to fulfill the requirements to obtain Senior Qualification Education.

### 2.1 Twente Educational Model (TEM)

As stated in the introduction the TEM was introduced in 2013 simultaneously for all BSc. programs [28, 29, 30, 31], following a pilot in the Biomedical Engineering program. Learner-Centered Teaching and active learning are the underlying philosophy. The TEM is a modularised program. In each module teaching and learning is offered thematically and integrated. The objective is for students to go for 15 European Credits per quartile in one go. Before the introduction of TEM the faculty of Engineering Technology already introduced Project Based Learning in 2001.

### 2.2 Theory of Learning and Systematic Analysis to Problem Solving

Vygotsky's sociocultural theory of cognitive development (constructivism) explains learning as a process of cognitive development in social contact [32]. He defines the concept of a Zone of Proximal Development. The borders of this zone are on the lower limit the level of analysis and problem solving reached by the learner without any help. At the upper limit the level a learner can achieve with the support of a skilled instructor. This interaction with a more knowledgeable other (MKO) is crucial in learning. This person may

be a teacher, a parent, an older adult, a coach, or even a peer. The role of the MKO is to provide the learner with the right quality and right quantity of support, where this level is adjusted in order to fit the students current performance. At first this may be direct instruction, e.g. making exercises on specific well organised forms. This can be seen as scaffold towards full understanding which can be removed when no longer needed, i.e. when the different steps are first known, so the learner is able to discuss them and reflect, and subsequently practiced enough that they are internalized. Vygotsky theory has affected many changes in educational systems through the increased importance given to the active role of students in their own learning process, and the encouragement of teacher student collaboration in a reciprocal learning experience.

Even though not specifically noted, Polya's 4 step problem analysis:

- Understand the problem (what is asked)
- Make a plan (that leads to the answer using division in subproblems e.g. by finding the right equations that have to be combined)
- Carry out the plan
- Look back at the solution (reflect)

can in fact be seen as a problem solving recipe that could have been based on a constructivism approach to learning to solve problems. In fact Polya was ahead of his time as he not only explains the process, he also extensively discusses the role of the teacher and learner, and his approach contains quite some elements of the innovations advocated in STEM teaching in the recent decades.

At the University of Twente in 1977 the then called centre for Educational Research and Development and the department of Applied Physics started a project "Problem solving in electromagnetism" with the aim to develop means which could be helpful to the students in learning how to tackle electromagnetism problems and reconstruct the course. The development is described by van Weeren et al. ([15]). The approach is formally based on the Gal'perin theory of learning [32, 33], which can be seen as a further development of Vygotsky's theory. To support the mental actions in the first phase of the learning actual forms for problem analysis were introduced to "force" the student to follow a specific path and help the teacher to give feedback to the learner and actually see the steps taken by the learner. Comparing the exam results in the year 1979-1980, to the results of the preceding years (with appropriate corrections) it was concluded that the approach significantly improved the results of the learners in tests. The course was taken by students in the four disciplines Chemistry, Mechanical Engineering, Electrical Engineering, and Applied Physics. This work was based on Mettes et al. ([14]) on reconstructing a thermodynamics course in the department of chemical engineering aimed at improving problem solving.

In the following years the specific attention for problem solving capabilities was quite widespread at the University of Twente, with particular strong advocates in the Mechanical Engineering undergraduate curriculum. The first year courses in statics and dynamics entirely evolved around the SPA concept. Students were still handed out specific forms on which to work out the exercises in working classes, with the first step invariably being the drawing of a so-called free body diagram (VLS). This is the graphical illustration used to visualize the applied forces, movements, and resulting reactions on a body in a given condition. In the past two decades the role of SPA in the curriculum has almost completely faded away.

A systematic analysis is the foremost step emphasized to teach problems solving. However, it assumes a particular order: analysis, development of a plan, execution of the plan, and verification/check of the results. The process takes as a starting point the data or quantity needed. A systematic analysis of this type is an excellent start, however, one of the characteristics of the problem solving process of a real expert is that it also follows different avenues. The expert also reasons from the data given and constructs a solution path forward, see [34]. Also, the expert is generally not focussed on a very specific result, but has a more general goal when constructing the path from what is given to what is needed. The plan made is also often constructed using previous experience and knowledge that combining certain steps into a plan will lead to a solution whereas others will lead to something too complex to solve. As explained in the introduction, this is what engineers tend to be good at. [34] is in fact a very nice example of Decoding the Discipline of Engineers.

### 3 Module Fluid Mechanics and Heat Transfer

The module "Fluid Mechanics and Heat Transfer" (201700127) is offered at the University of Twente in the third quarter of the second year of the BSc. program Mechanical Engineering. The module is directed at learning the physical mechanics and fundamental laws related to fluid motion and heat transfer, and the methods derived from it which are used in practice to answer numerous questions in engineering applications such as the forces by flow on structures, or the required rate of heat transfer needed to cool or heat an object or system. The Module consists of 2 courses and a project:

- **Fluid Mechanics I.**  
Fundamentals of fluid motion, conservation laws in integral and differential form, dimensional analysis and numbers. Learning goals are the ability to analyse a system and analytic computation of forces by fluid on structure using the fundament

laws. Solving the fluid velocity field in asymptotic (simplified) flow regimes from the Navier Stokes equations. Understanding of basics of compressible flow and the ability to use invariants, ability to manipulate partial differential equations of flow so as to analyse systems, and ability to carry out non-dimensional analysis for problems and relate the results to actual dimensional problems.

- **Heat Transfer.**

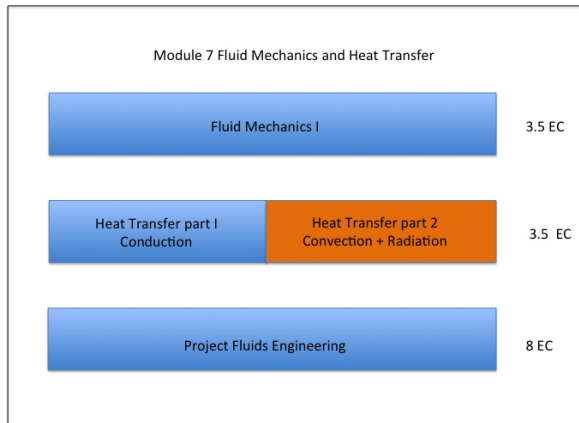
Knowing and understanding the fundamentals mechanisms of heat transfer (conduction, convection, radiation) the relevant non-dimensional parameters used in practice to characterize such problem for steady conditions, and being able to analyse heating/cooling problems using the empirical relations in terms of non-dimensional quantities for practically relevant problems from formulas or graphs. Unsteady heat conduction in solids. Basics of radiation heat transfer. Heat Transfer is subdivided in two parts which are given by different teachers. Part I: Conduction. Part II: Convection and Radiation.

- **Project Fluids Engineering.**

The project is a teamwork design project for a practically relevant application involving fluid mechanics and heat transfer. The aim is to achieve a deeper level of understanding of the course content by actual application. Project based learning is at the core of the Twente Education Model []. The design problem solved involves many other aspects than only fluid mechanics and heat transfer. An additional challenge for the students is to work as team, and organize the project both in terms of the division in subproblems (content) and their interrelation, as well as in dividing the work in the group, and ensure good communication. The groups are approximately 8 persons in size, and supervised by a staff member or student assistant. Examples of project topics are: Design of an anti-icing system for an aircraft wing, design of a heatshield for the Soyuz capsule returning from the International Space Station entering from the atmosphere, see Fig. 5, and the design of the cooling channels in the wall of the Vulcain V Ariane rocket engine.

#### Organization

The courses are 3.5 EC each, organized in 12 lectures with one exercise (working) class following each 2 lectures. In the exercise class students solve exercise problems from a reader [35] and book [36] under the supervision of the teacher and a student assistant. The heat transfer course is shared by two teachers, one part on conduction in various scenarios and the second part on heat transfer by fluid motion (convection) with different physical mechanisms driving the flow (natural versus forced convection) and elementary radiation, is given by the author. This second part consisting of



**Figure 4:** Overview of courses and project in Module 7 Fluid Mechanics and Heat Transfer. The second part of Heat Transfer indicated in orange is topic of the redesign study.

6 lectures and 3 working classes has been redesigned in the present study, see Figure 4. The project is also organized by the author.

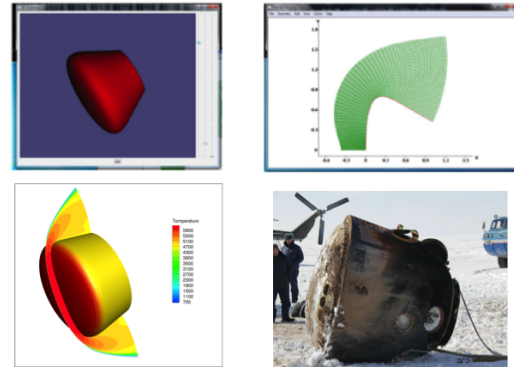
The number of students in the courses is generally 100-140, depending participation from other programs. The project of 8 EC is done by 80-100 students usually in groups of up to 9 persons. The project starts with a kick-off meeting in which the problem and its background are explained. For specific topics project lectures are planned. When possible an inspiring guest speaker specialized in the application is invited from industry or from knowledge institute. Andre Kuipers, the dutch astronaut was guest speaker in the project on Soyuz heat shield design.

### Course material

Fluid Mechanics I is based on a reader [35]. Heat transfer uses the textbook [36]. The material for the project is a project description providing background and assignment details and a first breakdown of subtopics. A starting set of relevant articles for different subtopics is provided on blackboard. For some specific tasks more complex computer “tools” (CFD software/programs) are supplied with instruction.

### Evaluation for Grading

The courses are evaluated with exams in which students have to solve a set of problems, characteristic for the different topics considered in the course. They need to analyse the problem, understand what is given and what is needed, see which part of the theory and associated formulas/equations can lead to the required answer, and obtain this answer correctly in units and in magnitude. The problems are very similar to the exercises in reader and book, which were practiced in the working classes.

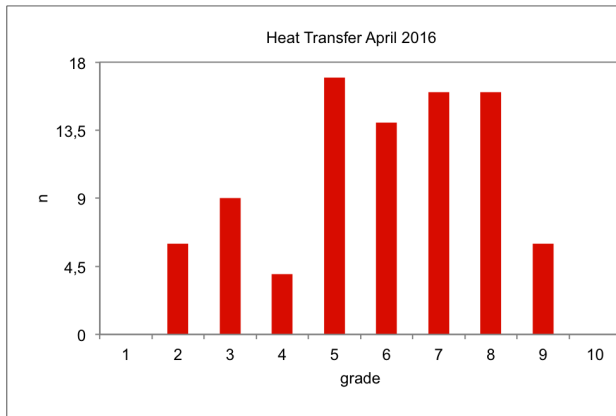


**Figure 5:** Impression of results obtained by students in a Fluid Engineering project: Computational model of Soyuz capsule during entry in atmosphere (top left), grid structure for computer calculation of flow (top right), computed temperature in the flow field in front of the capsule shortly after entry at Mach 20 needed as boundary condition in heat shield design (bottom left), and Soyuz capsule after landing with burned heatshield clearly visible.

Grading for each problem is based on the analysis, i.e. extracting the real question from the problem description, the strategy designed towards the answer and the correct equations used, the actual correctness of computation, and of the (sub)result in terms of dimension and correct value. For the course Heat Transfer the exam consists of two parts, each with a separate set of problems. The score that can be obtained for each part is 10 points. The final grade is determined by adding up the score of both parts and dividing by 2. The deliverable of the project is a group report which accounts for 50 % of the project grade. The other 50 % is determined by the individual score of students in a in a group exam in which 2 tutors ask questions about all aspects of the project and the relevant theory of fluid mechanics and heat transfer.

### Reference state

The module Fluid Mechanics and Heat Transfer is evaluated each year based on questionnaires by e-mail (SEQ). The evaluation reports are available ([37]). The questions relate to various aspects of the project, such as content, organization, relevance, challenging, availability of tutors, suitable for group work, grading, and the courses. On a scale of 5, in 2014-2015 the average grade for the entire module was 3.3 with the course Fluid Mechanics I scoring 3.2, Heat Transfer 3.7, and the project 3.0. The questionnaire was sent to 141 BSc. students and the response rate 18 %. In 2015-2016 the module scored 3.6 (105 students, response rate 40 %). In that year the courses scored 3.8 and 3.9 respectively. Critical remarks about the module relate mostly



**Figure 6:** Results Heat Transfer first exam course-year 2015-2016.

to aspects of the project such as availability of tutors. Positive remarks are made about the organization of the module, the clear relevance of the topic, the good relation between the courses and the project. The module is never considered “too difficult”, so it is apparently viewed “doable”. In this respect it is interesting to take a closer look at the exam scores, in particular those of Heat Transfer. For 2015-2016 the score is illustrated in Figure 6. These results are restricted to the first exam immediately following the courses, i.e. no resit data is included. 88 Mechanical Engineering students participated in the exam. Assuming a passing grade of 5.5 the number of students that has passed is 48 accounting for 55 %. This score already involves a minimum of 1 point always given so that in fact students can achieve 21 points.

### Problems observed

From the results of the evaluation and of the course exams it is seen that the module is evaluated positively and considered relevant and interesting but at the same time the percentage of students passing the course the first exam is relatively low. From the exam grading it shows that students apparently have much difficulty in solving the exam problems whereas they are to a large extent the same as the problems prescribed for the working class. In the grading it was seen that the students have significant difficulty to outline a “strategy” that will lead to the result, and finally finding or knowing the right “relation” for the convection heat transfer. This could indicate a lack of overview over this topic. A significant number of mistakes could easily have been avoided working systematically, and checking the results, including value and dimension. Taking a closer look at Fig: 6 there is a large group of students, i.e. 17 accounting for 20 % of the population that scored grade 5 which is close to the passing grade. If only half of these students would have scored a little better the passing grade would have been up to 65 %.

The conclusion is that apparently the “problem solving” capability is just not good enough. Two possible

reasons are that the topic has not received enough attention in the course, or that the students did not get enough (guided) practice themselves. As far as this latter assumption is concerned practicing problem solving is exactly what should have been done in the working classes. However, it is observed by the teaching staff that these working classes have a poor attendance, both for Fluid Mechanics I as well as for Heat Transfer. Typically right from the start less than 50 % of the registered students was observed to participate. Low working class attendance is confirmed by results of the evaluation questionnaire. 90 % of the respondents have indicated to have followed over 50 % of the lectures, whereas 51 % of the respondents indicates they have attended over 50 % of the working classes. This seems to indicate a motivational problem to attend the working classes, or insufficient realization of the importance of practice by actually “trying” and “doing” under supervision.

## 4 Redesign

Part II, the “convection and radiation” part of the heat transfer course has been redesigned. The first part “conduction” is not changed and maintains the classic teacher centered lectures with working classes only focussing on making exercise problems from the book under supervision. The aims of the redesign are to create a less teacher centered learning environment in which students are more motivated, attain a more active role in their own learning process, and in which the problem solving capability is improved, which should be reflected in the exam score. This end term, being able to solve problems, is maintained as this is an essential part of what engineers should be able to do. Analyse and solve a problem all the way to the correct numerical answer. A secondary goal is to achieve a lasting effect (deeper learning) for the following modules in the program.

Several measures have been implemented in the course year 2016-2017. The study has been repeated in the ongoing academic year 2017-2018 with some further fine-tuning. The measures taken are motivated by elements of constructivism theories of learning and the various “new” approaches advocated in STEM education in the past years.

### 4.1 Motivation/Preparation

Heat Transfer in Mechanical Engineering is often treated from the technical point of view, i.e. with technological examples, such as heating and cooling systems in processes or equipment. However, not all of this equipment is familiar to second year BSc. students. However, every living being on our planet is by evolution extremely well adapted to surviving in an atmosphere in which the living conditions are to a large extent determined by fluid mechanics and heat



transfer considerations. How do animals in the arctic stay warm ? Can you explain why a sea lion needs a huge layer of fat to protect itself from cold whereas a penguin only has feathers, whereas the conditions in which they live are the same. Also in our daily lives there are many examples. To bring the topic of heat transfer into the area of interest of the student before each lecture they are asked to fill out a short quiz on a google form with questions from "daily" (student) life. This quiz serves as a preparation for the lecture. Each student that has participated in all quizzes, attended the How to solve it sessions (see below) and participated in the model Systematic Problem Analysis exercise (see 4.6) is entitled to a bonus of 1 points (of 20) at the exam. Throughout any activity in the course teacher and student assistants should always clearly show motivation and enthusiasm crucial to stimulate student engagement and a supportive environment [43] [44]. In martial arts terminology this would be called "push (invite) by example". A final aspect that is taken from the many years of martial arts teaching is in the language used in teaching. In a learning process students are exposed to "someone already understanding" something "they have to learn", and prove this by passing some test. The "have to learn to pass" feeling should change to "want to learn". A positive intrinsic motivation to learn is probably the best driver and inevitably will lead to deeper learning. Teachers often try to reach out to students by confirming that "something is very difficult", and explain how much time and effort it cost them to grasp a particular concept, and that the only way for the student to get to understanding is by going through the same suffering. However, it is exactly these kind of statements that are not effective to make as they may often remove the topic or goal away from the Zone of Proximal Development of the student, i.e. beyond the reach. Instead of focussing on the goal the teacher can focus on each of the steps in the process, the fun of trying, and emphasizing the small success in steps. For example, the ability to make a good kick or a good punch in karate simply comes from making many kicks and punches, without thinking with each punch or kick if the fist was wrong or the foot was in the wrong position. Simply doing it with full motivation many times and being encouraged for the positive aspects of the effort and the intermediate results without having emphasized what is still "wrong" will eventually after a few thousand techniques by itself lead to improvement. A teacher should be constantly aware of the enormous effect of positive motivation in language.

## 4.2 Students as Partner

Students as partners [23] refers mostly to the teacher and students "learning together". In this study the topic has been interpreted differently. For the preparation and the running of the student assistants have been involved that have taken the course just over one year

ago. All teaching material, topics, and exercises have been reviewed taking into account their "learning experience" in the course. Difficulties encounters, topics that were still not clearly understood, topics that took a long time to understand, types of exercises that were interesting. The student assistants have been active through the entire part of the course, present at the lectures, formulating exercises and possible exam exercises, and assisting in the working classes. In this way it was attempted to ensure that the "gap" between the "teacher" and the "learner" would be smaller, i.e. that the students had contact with "role models" or "more knowledgeable others" that were closer to their level of knowledge which indirectly provides motivation that understanding the content is within their reach (ZPD).

## 4.3 Decoding the Discipline (DtD)

In section 2.2 it was already noted that experts solve problems systematically but not exactly in the same systematic approach as emphasized in teaching problem solving [34]. Experts in a field when solving a problem already use their "secret" knowledge that makes them master in the topic. In addition to the actual "content" teachers try to convey they should be aware of what experts (they) actually "do" and "know" when solving a problem themselves. Knowing this an expert (teacher) and transferring this in teaching it to students is the essence of Decoding the Discipline [24]. Often the expert is unconscious of some aspects that may be crucial to learning for the students. Finding out such aspects can be done by interviews with professionals in education, or otherwise (see [25]), or with students. Regarding , heat transfer by flow, e.g. part II on convection, the authors' research and teaching experience, shared experiences of colleagues and the learning experiences of the student assistants in their education so far, the biggest problem for students to problem solving is to do the first analysis of the problem, and make the plan leading to the answer.

Heat transfer is fully determined by the type of flow. Is the flow inside an object, or is it around an object. Is the flow laminar, or turbulent. Is the flow externally driven, i.e. by some ventilator or is the flow occurring "naturally", e.g. driven by density variation induced by temperature such as warm air rising above a candle. Classifying the flow as one of these types is the first and most important step. Next one needs to understand the concept of a heat transfer coefficient being a problem dependent parameter, and not a material constant. Then the major point is to find its value for a particular case. Fluid mechanics problems can often not be solved analytically so for heat transfer coefficient values one relies on data from experiments which are often captured in formula's called "correlation". This correlation is always given in terms of dimensionless parameters. Dimensionless parameters are a fundamental aspect

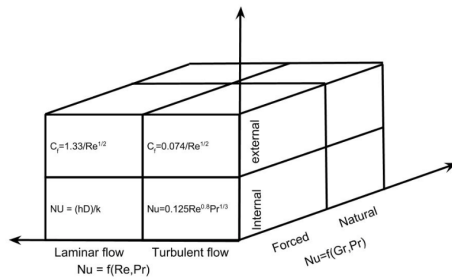


Figure 7: Building block scheme of convection problems.

to understanding fluid mechanics. They represent the strength of the physical mechanism that drives the flow, they allow the use of the results obtained for one particular case e.g. an object of a certain size, for another case with the same object in a flow of different speed or the object of different size. Understanding dimensionless numbers is a real Threshold Learning Concept in fluid mechanics (see section 4.4).

In heat transfer textbooks and handbooks all correlations are given in terms of these dimensionless numbers. There are different correlations for the different types of flow, and each correlation has a range of validity. One of the biggest problems for students is to use when to use which "formula" as they usually call it. The basic answer is the flow characterization and this has been emphasized in the course. The general "recipe" to determine a heat transfer coefficient is then:

- determine the type of flow, internal, or external. This can be seen from the application
- determine if the flow is driven or natural (forced or natural convection). This can be seen from the given configuration or data.
- determine if the nature of the flow, laminar or turbulent. This can be done using criteria often based on the Reynolds number, one of the dimensionless numbers
- Having dissected the problem in this way, now look for the right correlation in your textbook with the right range of validity. Represent your input data in dimensionless form. Input them in the correlation. Compute "back" to the real data.

This procedure, or the *code of the discipline of determining heat transfer by flow*, in fact represents the overview of the entire course and the blueprint that can be used in any problem. This has been emphasized to the students in the lectures by referring to it every lecture, and using as a memorizer a "building block of convection problem" scheme, see Figure 7.

#### 4.4 Threshold Learning Concepts (TLC)

Meyer and Land [38, 39] in pursuing research as part of a UK research project to Enhancing Teaching-Learning Environments observed that in the field of

economics certain concepts were held, central to mastery the subject. They referred to these as "threshold" because they had specific features in common. In a very accessible short paper Cousin [40] states that rather than stuffing a curriculum and expecting students to absorb and reproduce this bulk, focus on threshold concepts helps teachers "to make refined decisions about what is fundamental to a of the subject they are teaching, see also [41]. Meyer and Land present several key characteristics of a threshold concept:

- Grasping a threshold concept is transformative.
- A threshold concept is irreversible. Once understood the learner is unlikely to forget it.
- It is integrative, and exposes hidden interrelatedness of the field (or phenomenon) Mastery of the concept allows the learner to make connections that were until then hidden from his/her view or perspective.
- It involves aspects of troublesome knowledge, i.e. appears to be counter-intuitive, alien, or seemingly incoherent. In short, "common sense" or existing "intuitive" ideas of the learner can inhibit understanding a threshold concept. As reversing these intuitive ideas causes uncomfortable emotional repositioning, this adds to the difficulty of learning.

Often understanding a threshold concept requires "several passes". Its understanding can not be "forced" by studying. At some point with the right trigger offered in the explanation it just "happens". A threshold concept is like a portal that opens in only one direction, and the challenge for the teacher is to help the student feel this direction, open it, and pass through.

A topic in fluid mechanics and heat transfer that more than satisfies each of these criteria are the so-called Dimensionless Numbers. This can easily be verified by many researchers, professionals, teachers, and learners in the field. Dimensionless numbers represent the relative magnitude of terms in the equation of flow, and thereby determine the nature of the flow. The Reynolds number is the ratio of the viscous and the inertia terms in the momentum equation. When this number is large, the flow is driven by inertia. When it is small, it is driven by viscous forces. Dimensionless numbers enable translating results from one problem to the same problem with different parameter values but essentially the same physics. They also allow optimal representation of data for use by other researchers and engineers. It also allows one to translate real scale results to model scale tests needed to be done and these results back to real scale results. Finally any correlation in heat transfer is given in terms of the dimensionless numbers.

To help open the door various measures have been taken. Firstly a short memo has been written on how dimensionless numbers appear in the equations as a result of scaling. Secondly, in the classes the meaning of the most important dimensionless numbers is

explained in detail, and, most important, in a playful way verbally practiced, that is, by asking 10 students in a row “what is the meaning of the Reynolds number”. At first this raises a slight embarrassment owing to being asked such a simple task in public. However, repeating a sentence yourself creates memorizing, and opens a way to understanding. Having had 10 students try to repeat the sentence “The Reynolds number represents the ratio of the convective to the viscous terms in the momentum equation” which after a few times simply became fun, instills something in the memory of all. The next lecture almost all students can answer the question. At first this will only be repetition, and not represent their own understanding but in the following courses this understanding will develop because the seed of the right mental storage has been sown.

It is interesting to note that in academic teaching learners and teachers mostly use their mind. As was noted with active learning, one may achieve deeper learning when actually “try and do”. Doing we can also interpret as using verbal expression. Indeed a very old-fashioned way of learning i.e. many of the more mature generation will remember learning tables of multiplication by repetition out loud. Indeed, just repeating may not instill the required deep insight, but in the same way as using specific forced forms in the initial part of the teaching process. Also, when firefighters learn to enter houses or rooms they have a specific procedure. They always go in pairs, follow the wall on one side, feeling the wall with the back of the hand to recognize identification points. Anything recognized will be mentioned out loud: “wall”, “closet”, “table”, and each is confirmed by the second person. Having completed the search of a room, or found a victim, they turn around, and almost by magic, the list of items in the mind also turns around and they walk back knowing exactly what to pass on the way to the exit and where the exit is located. This experience by the author and many similar experiences in martial arts related practices initiated the above explained little “repetition experiment” to help learn the meaning of dimensionless numbers.

Finally, in martial arts one has degrees of blackbelts. first degree, second degree, and so on. Traditionally in Japanese culture there are 5 degrees of quality, and in martial arts five degrees of mastery. The transition from each degree to the next requires passing through a conceptual change. In fact it requires understanding a threshold concept [42].

#### 4.5 Lectures

The “classic” teacher centered lectures have been reformed including many everyday and technical examples from various fields. Teacher and student assistants should always clearly show motivation and enthusiasm crucial to stimulate student engagement and a supportive environment [43] [44]. In martial arts

terminology this is called “push by example”.

#### 4.6 How to solve it session

Problem solving is placed central in the working class which has been transformed and renamed into “How to Solve it ” session. The first 10 minutes of the How to Solve it class the google form quiz answers are discussed. As google form allows showing grouped results of the answers this provides valuable information about the answers (statistics) are given, which can be used in the discussion to reflect with the students, and to learn their reasoning. The discussion is without a “right” or “wrong” and in fact serves as a prelude to the analysis of exercise problems.

The second part of the working class consists of a model problem for which the students work on how to solve it for a specific period of time. The problem is given in an applied form:

*On a warm sunny evening an unexpected visitor arrives. You want to serve the visitor a cool drink. However, you only have one can that is not in the fridge. If you just put it in the fridge it may take too long to cool to a refreshing temperature. You decide to place a small fan in the fridge to make the air move. Determine an approach that allows you to compute how much faster the softdrink reaches a specified acceptable temperature due to the fan blowing*

This exercise potentially contains all aspects of conduction and of both natural and forced convection, and the “best” approach is not immediately clear. It is up to the students to see this, and decide what could be the most dominant physical phenomena, and which theory and equations will lead to an answer. They have to apply a systematic problem analysis according to the SPA method. They also have to work in a small group to benefit from the discussion (active problem solving [20], peer instruction [45]). For the teaching staff to verify the result in terms of capability the resulting analysis needs to be handed in hand-written but it is made clear that it will not be graded. To the contrary, students that have filled out the quiz (google form), have attended the How to Solve it session, AND handed in their analysis are entitled to a 0.5 point bonus in the exam (1 point out of 20). The objective is to simply expose students to systematic problem analysis and have them grapple with it. It is expected that simply being exposed and having tried is already a significant step getting to know the approach and will contribute to its use and internalization. Student assistant and teacher monitor progress and assist. In the second year the redesign was executed, preprinted SPA forms were used ,with space for the different steps of the approach, as done in [15].

The third part of the working class is the time to practice exercises from the book, also under guidance of student assistants and teacher.

## 4.7 Course Material

The same course book is used. Regarding the Systematic Problem Analysis a short manual in which each of the steps and motivation are explained is provided in digital form. Also specific forms (in paper) have been made to use in the How to Solve it sessions when making exercises. The choice of paper is deliberate. Students have to hand in the model analysis exercise in handwriting. The idea of the form is taken from the original introduction of SPA methods at the University of Twente [15], and exactly aligns with the Vigotsky theory of learning, i.e. using the form will help the student in an early phase of learning to practice the steps and get familiar, and to help internalization of the approach. To help practice exercises and preparation for the exam a collection of the relevant exercises of the second part of Heat Transfer in the exams of the past 3 years, with the answers written in an extensive way motivating and explaining each step is provided electronically.

Finally, as part of the effort to reduce the Threshold Learning Concept of dimensionless numbers a topic which is not well treated in the course book, a handout is provided showing the scaling of the Naviers Stokes equations to obtain the Reynolds numbers to help understand the meaning of dimensionless numbers as ratio of terms representing different physical mechanisms in the flow.

## 4.8 Evaluation for Grading

In the evaluation nothing is changed. A regular exam of exercises representing realistic heat transfer problems. This is a deliberate choice as such exercises do represent the engineering reality where problem analysis yielding in a plan, followed by calculation, and check of the results for value and dimension should in the professional practice be routine. For example in a design problem one should be able to end up with a correct answer such as the required fluid velocity to achieve a given heat transfer for heating of cooling. The novelty in the evaluation is that students that have filled out the all quizzes (google form), and have handed in all their description of an approach leading to the solution of the problem solving exercises are entitled to a 1 point (out of 20) bonus in the exam. Note that in the original exam evaluation this bonus was also present. The main point in the redesign is that it is explicitly used to provide motivation for the students to do what in the end should help them gain much more than only this bonus.

## 5 Results

The redesign was implemented in academic year 2016-2017, with the first “practice run” in februari-march 2017. Test results are the exam results, the results of

the evaluation of the module by e-mail questionnaire, the results of a panel discussion with a delegation of students, and finally an interview carried out by Dr. J. van den Berg (CELT, UTwente) with a few students that scored very poorly. The idea of this interview is to see if an “independent” expert can yield information relevant for the teacher regarding thresholds concepts or other education aspects relevant for future editions.

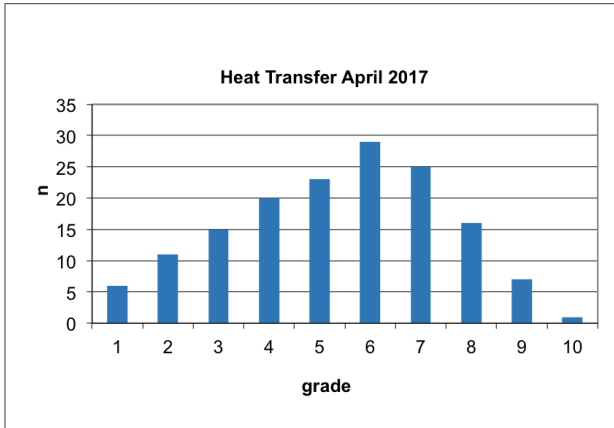
### 5.1 Exam scores

Figure 8 shows the results of the exam of Heat Transfer taken in april 2017 immediately after the course. Number of participants was 153. This includes a significant contribution of students that probably have retaken the course or may not have been of the ME programme. 78 students obtained a score in excess of 5.5 giving a passing rate of 51 %. The average grade was 5.9 The bonus 0.5 point (out of 10) was earned by 57 students. The quizzes were filled out by roughly 90 people, and yielded interesting results in the views students had on particular problems not knowing/understanding the relevant theory yet. The How to Solve it sessions were well attended, about 100 people, and very lively with a positive atmosphere. This was a huge difference compared to the previous years. The time spent on the model systematic analysis exercise was often longer than planned, so that the time left to practice actual exercises from the book was smaller. This could have been kept in check better. However, often students were eager to finish it, and breaking this attitude was not considered a very good idea. This was a huge difference with the previous years. The passing score of 51 % is not larger than the previous year. However the average grade itself is larger. For reference, the passing grade of the Fluid Mechanics I course was 67 % with an average grade of 6.3.

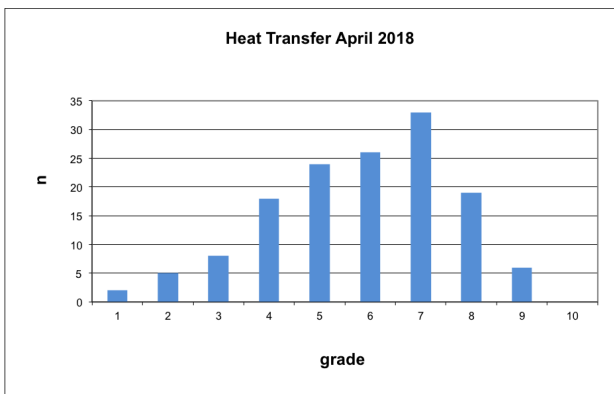
Figure 9 shows the result of the Heat Transfer exam taken in april 2018, immediately after the course. The number of participants was 141. 60 % passed the threshold of 5.5 points (out of 10) The averages grade of all participants was 5.8, i.e. slightly lower than the previous year. 60 people received full bonus for the quiz forms and handing in the model SPA analysis. Again the How to Solve it sessions were well attended and appreciated. Formal SEQ or SET/ME evaluation results were not yet available at the time of writing. The increased passing grade is off course motivating, particularly when it is noted that the passing grade of the Fluid Mechanics course was only 33 % with an average grade of 4.54 (138 participants, 46 passed) and that for this course the appreciation of the lectures is very high but the attendance of the working classes was very low.

### 5.2 Student evaluation

In the 2016-2017 the SEQ evaluation of the Module 7 performed by e-mail questionnaire the courses Fluid



**Figure 8:** Results Heat Transfer first exam course-year 2016-2017.



**Figure 9:** Results Heat Transfer first exam course-year 2017-2018.

Mechanics I and Heat Transfer received an average grade of 4.1 and 3.7 (on a scale of 5) respectively. The questionnaire was sent to 114 students and returned by 26. The response rate of 23 % was considered to give reliable results. The (translated) summary of the result is that the module was considered sufficiently challenging and the students have the impression they earned much from teachers, student assistants and tutors (in the project). The module is considered to be well organized, although there are some differences of opinion. Generally the integration of the content of the courses in the project is considered valuable, even though it is noted that the treatment of particular aspects of "content" in the courses is not always ideally timed with the need of this content in the project. This is an issue that is recognized by the staff as being an intrinsic challenge of the TEM system particularly visible in Module 7 where students have to work on a realistic Fluid Mechanics and Heat Transfer problem, where they don't know anything about either topic yet. This difficulty can not be resolved within the TEM system unless project and courses are staggered relative to the project. At present the improvised solution is to design the project such that in the introductory phase aspects of the design are studied that can be evaluated with previous knowledge, such as trajectory computations of a rocket using the equations of mechanics. One could however argue that an important driver to learning and deeper understanding is a "need to know". When students have already thought about a topic, they will be much more receptive to the material when it is presented in the courses.

The courses were evaluated separately by the evaluation committee ME/SET ([37]). Regarding the different parts of the module the Heat Transfer course scores 3.7 on a scale of 5 which is considered "good" for a BSc. module part. The questionnaire was sent to 114 students and the response rate 33 %. High scores were given to the relevance of the topic for the education (4.3) and to the availability of sufficient exercise problems that clarified the course content (theory) (4.2). The lectures apparently were not deemed by all to clarify the content of the course (3.4) and particularly interesting is that asked if practicing the systematic problem analysis helped improve the capability to make exercises the students were also relatively critical (3.4). This answer needs to be viewed in the context of the fact that the response rate is rather limited (33 %) , and that the real improvement in the short run may not be realized yet by the students themselves. Regarding the lectures contradicting statements were given. On the one hand students valued the very structured nature of the teacher centered lectures of part I as positive, and considered the discussions which were entered in the lectures of part II as part of the redesign as taking away structure. At the same time the way of teaching of part II was experienced more positive because of the more intense interaction with the students and the many clarifying specific examples given. In view of the fact

that increased participation was one of the objectives of the redesign this can be valued as positive.

In addition to the SEQ evaluation of the module, and the ME/SET evaluation committee of the course also a panel discussion was organized about the module similar comments were made. In this evaluation the How to solve it form of the working classes was generally evaluated as positive. However, it was noted that the time left for actually practicing model problems from the book was too small. This may be remedied by adding additional sessions to the course. In general the second part of the course was considered "better" than the first part.

### 5.3 Panel discussion

Based on the research and teaching and learning experience of the author, shared experiences with colleagues and the learning experiences of the student assistants in their education so far specific aspects were chosen on which to build the redesign. In fact the "Discipline of Solving Heat Transfer problems" was decoded resulting in the observation that key to problem solving capability is flow classification. Understanding the types of flows hinges on the understanding of the concept of dimensionless numbers which was identified as the key Threshold Concept. Particularly as they are also essential in forming the plan to solve the problem as they determine which equations or formulas need to be combined to come to the answer. Finally, they also play a role as all equations needed are given in terms of these numbers. However, this vision is already based on being educated in the field, there is a possibility that there are other Threshold Concepts which are missed which may have troubled the students.

It was speculated that students who scored particularly poor in the exam may be able to (help) identify possible other Threshold Concepts than seen by the "experts". Another possibility was that there was no additional concept but that it were the mathematical/calculational skills that held the students back from good results in the test. To investigate this a panel discussion was organized with Dr. J. van den Berg (CELT) as independent panel leader. The discussion involved 5 students. The author and student assistants were on purpose not present. The results of this panel discussion have been recorded [46]. Based on these notes a few observations were made. The students did not clearly distinguish between the Fluid Mechanics course and the Heat Transfer course and their comments were mostly comparatively. Specific remarks were made about the exam questions of part I. Most of the difficulties mentioned can be traced back to the flow classification and already identified threshold concept of the dimensionless numbers. Apart from this conclusion the panel discussion did not indicate other threshold concepts, nor that mathematical or calculational skills were the problem. An interesting point noted in [46] however is that the students participating

in the discussion had the tendency not to be present at the lectures.

## 6 Conclusion

To improve the engineering ability of students to model and solve practically relevant problems related to heat transfer systematically, obtain realistic answers, and obtain better scores at regular exams consisting of such type of problem exercises, as well as achieve a deeper learning the heat transfer course of the 2nd year BSc. curriculum in Mechanical Engineering in the faculty of Engineering Technology of the University of Twente, was redesigned. The redesign involved reintroduction of Systematic Problem Analysis as a main concept, and was further done using concepts of Decoding the Disciplines, Threshold Learning, Active learning, Students as Partners, and has resulted in a new learning environment and experience for students and teacher which was positively evaluated. The percentage of students passing the first exam after the course was increased at first only moderately increased but in the second academic season a major improvement was seen. This may indicate that the problem solving capability was positively affected as was aimed for, but it is too early to conclude that from only two trials. Nevertheless, these positive results, the experience of the entire process of redesign and its implementation and the active interaction with students and student assistants stimulate further development possibly also extending to other parts of the module.

## 7 Acknowledgement

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difficult for the students to understand. Their “student partner” role has been essential in the process.

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## 8 About the author

The author obtained his MSc. (1987, cum laude) in Mechanical Engineering from the University of Twente, and PhD.(1991) in Tribology (Elastohydrodynamic Lubrication). He been a visiting scientist at the Weizmann Institute of Science, Rehovot, Israel doing post-doctoral research in Fluid Mechanics and Applied Mathematics, combined with a position as assistant professor at the University of Twente. Since 2014 the author chairs the research group Engineering Fluid Dynamics in the faculty of Engineering Technology, leading research and education in particular the MSc. program Thermal Fluid Engineering. The authors’ teaching career involves BSc. and MSc. courses in various subfields of fluid mechanics. In addition to this academic teaching experience the author the author holds a 3rd degree black-belt (Sandán) in Shotokan karate with a teaching experience of some 20 years to both adults and children.

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