INVESTIGATING LEARNING AND IMPROVING TEACHING IN ENGINEERING THERMODYNAMICS GUIDED BY CONSTRUCTIVE ALIGNMENT AND COMPETENCY MODELING:

PART I. IMPROVING OUR LEARNING ENVIRONMENT – HOW WE SUPPORT STUDENT LEARNING

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INTRODUCTION

In an effort to review our course on engineering thermodynamics, perceived as difficult by engineering students, we asked ourselves: *How can we create and constantly improve a quality learning environment?* Starting from these fundamental questions, we present our one-year course on engineering thermodynamics at the University of Stuttgart as a case study in which we propose several approaches on how to support student learning. We draw our insights from an extensive student survey regarding learning and study habits and student achievements, conducted parallel to our course in 2014/2015.[1,2] The survey results include statements from more than 1000 students regarding their perception of the course, their learning preferences, and several test results.

What do we actually mean when we talk about the improvement of a learning environment? In this paper we use *learning environment* in a broader sense than merely physical spaces, media tools and learning materials, opportunities for social interaction, course design, and the structure of the study program as a whole; the term also implies emotional aspects, like pressure to achieve, feedback and error culture, exam anxiety, and further surrounding conditions.

From the students' perspective the learning environment is a blurry and broad thing built from their life circumstances, including their general studying conditions and their subjective constructions of reality. From a teacher's perspective it is usually perceived in a narrow sense, focusing on the aspects of a course that can be shaped and controlled in a classroom situation, including, to some degree, self-study and learning activities outside of the actual classroom situation. For both perspectives *improving* the learning environment means reducing obstacles to the learning process, which constitutes our primary improvement approach.

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In this paper we aim to introduce several ways to identify and tackle learning obstacles and adverse aspects of the learning environment, as far as our scope for action goes, in order to support student learning and the achievement of the intended learning outcomes of our course. Some things, however, are not considered in this paper, e.g., the actual classroom design or group activities in tutorials. Also, insight into the nature of students' private self-study in our course is limited to answers in our survey.

This manuscript is structured as follows. We begin with an important reflection on what kinds of competencies we wish to convey to our students and – equally important – what kind of competencies are actually relevant for successfully passing our course. We introduce a competency model of a different kind, one that takes on the student perspective (based on the students' survey). Next, we offer a brief insight into how our course on engineering thermodynamics is designed, following the idea of *constructive alignment*. This includes the intended learning outcomes, subject topics, course design, and, to a limited extent, exam design. The core element of this manuscript highlights decision-relevant survey findings that help us identify crucial aspects of our students' learning environment and learning activities, and offers guidance for improving our learning environment. This includes empirical insights into students' learning preferences and different ways of problem solving. We introduce cognitive apprenticeship and present some results of an extensive statistical evaluation of our exam quality. Finally, we summarize major results of our critical review of our course design and learning environment.

The second part of our series (Braun et al.[3]) shifts the focus to the question "*Do we test the competencies we want to convey to our students?*" by investigating the empirical competency-structure of the final exam with insights from a probabilistic analysis and survey results. It expands on the possibility to apply item response theory as a statistical method for the in-depth analysis of exam quality and competency measurement. While some of the results of the second part are also of importance to this manuscript, they are only briefly touched upon here and will be discussed in more detail in the second part.

COMPETENCY FROM THE STUDENTS' PERSPECTIVE

Competency is a crucial aspect of the learning environment as outlined above. The learning environment supports and directs the learning activities of students towards the achievement of the intended learning outcomes, and thus the achievement of certain competencies. Improving the learning environment means increasing the chance of a successful achievement of certain competencies.

Competencies in Engineering Education

The description of competencies is usually based on a general concept of competency. The definition introduced by Weinert [4] is one of the most influential ones. It has been successfully adapted to engineering education, and recent years have seen several national and international research efforts on competency modeling in engineering education.[5-7] A general outline of competencies in engineering education is given in Table 1.

TABLE 1
Domain-specific and generic competencies as often presented by general educational theory and in research on engineering education. [8-12]

Domain-specific competencies
Domain-specific knowledge (declarative, procedural, conditional, functional).[13]
Domain-specific problem solving (application of procedures for dealing with problematic situations).
Domain-specific methods (use of specific tools).
Generic competencies
Motivation and volition (e.g., interest, engagement, decision-making).
Social competency (e.g., social integration, relationships, ability to deal with conflicts).
Personal competency (e.g., self-organization, time-management, meta-cognition, emotional control, self-directed learning).
Generic methodological competency (e.g., universal methods for the accomplishment of problematic situations without any domain-specific relation).
Values (e.g., attitudes and beliefs about people, groups, topics, behavior and so forth; usually tied to religious, political, cultural, or vocational topics).
Psychological dispositions (e.g., rather stable psychological traits, like intelligence or the big five personality traits).

However, when we turned to improving our students' learning environment, we realized that the typical competency model was missing an important aspect: the students' perspective. Students should have a say in it! This is not to say that students should define the syllabus or the intended learning outcome. However, they are the experts on how they actually shape their learning activities, how they achieve and sustain motivation, how they organize themselves, and so forth. We wanted to have a better understanding of what competencies are deemed relevant and *actually* achieved by our students. We wanted to acknowledge the students' perspective on the learning process and how *they* successfully complete our course on engineering thermodynamics.

In other words, we aimed for a competency model that reflected not only the intended learning outcomes and some generic competencies from the literature, but also the empirical competencies necessary for our students to tackle the whole study situation surrounding our course. Therefore, we conducted an extensive survey on study behavior and learning activities as well as in-depth statistical analysis of our exams.[1-3] In Figure 1, the final results of this empirically informed competency model are illustrated. They combine aspects from a general theory on competency and research on domain specific competencies in engineering education, as well as results from our own empirical research into our students' learning activities and perspectives on the study situation. Following Figure 1, we explain some important dimensions in more detail.

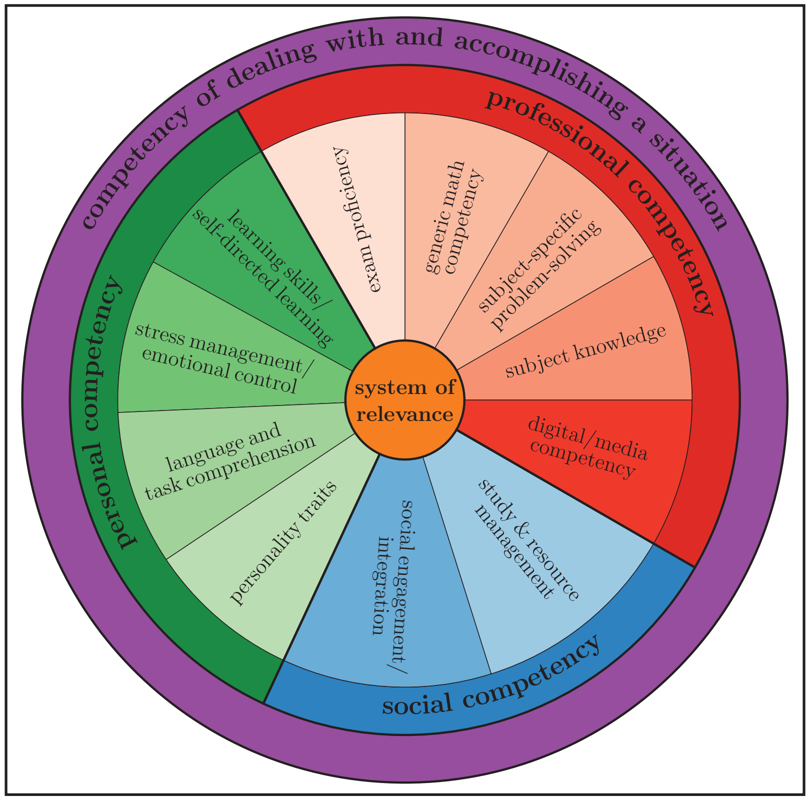

Figure 1. *An empirically based competency model showing different dimensions of students' competency for our engineering thermodynamics course. Framed by a general understanding of competency as the ability to successfully deal with a given situation (outer ring band, paragraph a), we propose three major dimensions of competency: personal (paragraph d), social (paragraph e), and professional competency (paragraph c). The inner slices represent sub-dimensions of each major dimension. They are based on theoretical considerations and our empirical results. The system of relevance (center, paragraph b) represents the important aspects of motivation, interest, volition, and so forth.*

Competency Model for Engineering Thermodynamics

a. **Dealing with and accomplishing a situation.** We define competency as a holistic trait of students who are able to successfully complete our one-year course on engineering thermodynamics. Dealing with this situation does not only include the exam performance; the necessary competency also extends to the learning environment, personal and social conditions, and so on.

b. **System of relevance.** The situation as a whole is enclosed by conditions of subjective relevance. Students' interests and motivations as well as their systems of relevance (reaching from daily routines to long-term plans on biographical and professional development) are something we see as a comprehensive aspect that is important in every dimension of competency. Here we consider the motivational structures as a universal part of the competency model, not as a mere subdimension of, e.g., personality.

c. **Professional competency.** In engineering thermodynamics, professional competency is represented, among other things, by knowledge of the covered subject matter (see Figure 4), and may be further described in terms of declarative and procedural knowledge.[13] This includes fragmented memorized content, like definitions or descriptions, but also knowledge on procedures, such as drawing a diagram or applying a balance equation. As conditional knowledge, it extends to knowing when certain knowledge is to be used for a certain objective. *Subject-specific problem solving* (see Table 4) is a crucial part in every vocational or academic education. This includes conceptual understanding, finding the right modeling approach, and solving discipline-specific problems accordingly. Due to the importance of mathematics as an indispensable foundation, it is appropriate to include generic mathematical competency as a dedicated sub-competency as well. Students must be able to communicate successfully and efficiently through mathematics. We shall also include exam proficiency. By this we mean the students' capability of coping with the exam (or other tests) in an efficient way.

In some cases this pragmatic approach competes with conceptual understanding. We will discuss this further in the results section. Nevertheless, if we want an empirical description of the students' competency for successfully passing our course, we cannot exclude their ability to deal with the exam situation. Since this also includes training for fast routines and memorization of standard procedures, we decide to define it as part of the professional competency. Finally, we also include digital/media competency as a sub-dimension of professional competency, since with the increase of blended and online learning activities, the correct use thereof is becoming increasingly important.

d. Personal competency. From our qualitative research, we found that even though we provide many guided learning opportunities, students' learning skills and their ability to achieve self-directed and motivated learning are very important for study success. From psychological and educational research, we also add emotional control and stress management as well as language and task comprehension as sub-dimensions of personal competency. The examination situation in particular requires mental strength and strategies for coping with stress and emotions. This extends to situations of unavoidable decision-making or conflicting interests.

e. Social competency. Going out and participating in learning opportunities as social situations is another dimension of competency that cannot be ignored. Good examples include our guided tutorials and informal learning groups. Social engagement goes even further. It means getting involved in student life and the culture that defines all the small habits, big values, and the system of relevance of the discipline in question. More attention has recently been paid to study and resource management in engineering education.[14] In our course we found that managing different competing study requirements, exams, and study projects is essential. Many students reported that the biggest problem was not the difficulty of the thermodynamic subject matters, but the management of different expectations and deadlines of various courses.

Synopsis of Our Competency Model

This concludes the brief introduction of a competency model for our engineering thermodynamics course. Since it is an empirically informed model that acknowledges the students' perspective on accomplishing the study situation, we accept the reality of student learning. This also means that we have to acknowledge the reality of certain strategies for exam proficiency and surface level understanding, even though we facilitate and strive for a deep level understanding and achievement of our domain specific competencies. During our quest for an improved learning environment, this evidence-based competency model greatly improved our perception of the study situation and allowed for a well-structured critical review of our course on engineering thermodynamics. The next section introduces a basic outline of our course structure and its content with references to the different dimensions of the introduced competency model.

COURSE DESIGN OF ENGINEERING THERMODYNAMICS

In this section we present some basic details on how our course on engineering thermodynamics is designed, what intended learning outcomes are proposed, and how the final exam is structured. We focus on aspects that are necessary or helpful in understanding what steps we have taken to improve our learning environment and support student learning. A learning environment is greatly influenced by the design of a course, the intended learning outcomes, and the structure of the final exam, and if we are to conduct a critical review of our course, we need to reflect on the underlying relationships among these aspects. The concept of *constructive alignment* proposed by Biggs and Tang [13] provides us with a very useful framework for this endeavor.

Constructive Alignment

Constructive alignment helps us to align the learning objectives (intended learning outcomes) with the covered subject matter, the learning activities specified in the course structure, as well as the final exam. Our *learning objective*s describe the knowledge and competencies we want to convey to our students. They are a subset of the *professional competencies* depicted in Figure 1; closely coinciding with subject knowledge and *subject-specific problem solving*.

Figure 2 illustrates the basic idea of *constructive alignment*. Teachers and learners are placed in a complex, situated environment in which the central aspects of the learning process should be balanced (*aligned*) against each other. In this sense, *constructive alignment* is a guideline for course design, evaluation, creation of learning environments, learning opportunities, and exam design. As Figure 2 indicates, examination, learning objectives, and learning activities all have an impact on each other.

The exam must serve the learning objectives, which also define what teaching and learning activities are appropriate in order to achieve the intended competencies and make them visible in the classroom and in the exam. Testing something that has not been practiced before or failing to design a test that reflects the intended levels of understanding leads to misalignment. Following the learning theory of Biggs and Tang,[13] teaching should help students to achieve a rich and deep level of understanding, not merely a surface level (e.g., *dealing with the problem* instead of *dealing with the test*).

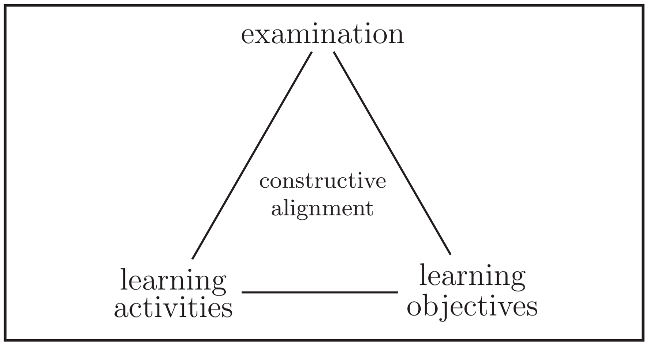

Figure 2*. General features of the constructive alignment framework interlinking learning objectives, learning activities, and examination.*

In order to design an aligned course on engineering thermodynamics, we follow the basic process shown in Figure 3. First, the learning objectives are defined, including the taxonomy levels (describe, explain, apply, assess, evaluate) as well as the desired knowledge level (unistructural, multistructural, relational, extended abstract).[13] In a second step the examination style has to be designed with the intended learning objectives in mind. Finally, the curriculum and the appropriate teaching and learning methods are developed. This sets up the stage for further details of the learning environment and any measures for its improvement.

With regard to the competency model shown in Figure 1, *constructive alignment* and basic course design are primarily concerned with the professional competencies, the selection of topics and subject matter, and media competency (ability to use learning materials in a variety of formats including digital, print, and blended learning), as well as the general setting of social learning and interaction within and outside of the classroom situation. The following sections present the intended learning outcomes, the subject matter, course and exam design.

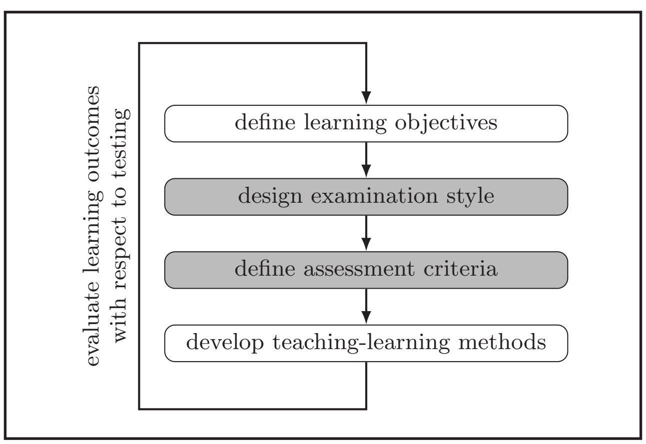

Figure 3*. Illustration of the implementation of constructive alignment for a course, including a control loop for quality assurance. It should be emphasized that the examination design (shaded nodes) takes place prior to the development of the teaching strategies.*

Learning Objectives and the Subject of Engineering Thermodynamics

The learning objectives of our course *Engineering Thermodynamics 1/2,* as stated in the syllabus, are provided in Table 2. They also describe the basic overall professional competencies we try to facilitate in our students (Figure 1). The *structure of the observed learning outcome* (SOLO) taxonomy [13] (pp. 81-94) classifies them as rather complex (conditional knowledge; multistructural and relational understanding).

TABLE 2
The learning objectives of the course *Engineering Thermodynamics 1/2* as specified in the syllabus.

	Learning Objectives
1.	Students can explain basic thermodynamic concepts and are able to independently formulate practical problems in basic thermodynamic quantities.
2.	Students are able to evaluate energy conversion in technical processes on the basis of system abstraction by using various tools of thermodynamic modeling, such as conservation/balance equations, equations of state and physical property models.
3.	Students are able to independently apply the second law of thermodynamics to thermodynamic processes, in particular to the calculation of thermodynamic efficiency of processes.
4.	The combination of the concepts of thermodynamic modeling enables the students to formulate more advanced solution approaches.

The learning objectives are important but still somewhat abstract and raise the question on what subject matter actually needs to be covered in such a course. They are listed in Table 3.

Unlike the abstract learning objectives, we can easily visualize the covered subject matters as fields of subject knowledge as depicted in Figure 4. Thermodynamic fundamentals form the foundation of the structure. These include the differentiation between thermal and caloric state functions and process quantities (the difference between internal energy and enthalpy, entropy and exergy in contrast to heat and work), definition and the difference between different kinds of systems (e.g., open, closed and stationary flow systems), and the description of conservation/balance equations (first and second law of thermodynamics and the exergy balance).

TABLE 3 Subject matters covered in the course Engineering Thermodynamics 1/2 as specified in the syllabus.	
	Covered Subject Matter
1.	The laws of thermodynamics for energy and material conversion
2.	Principles of thermodynamic modeling
3.	Thermodynamic processes
4.	Thermal and caloric state functions in contrast to process quantities
5.	Equations of state and physical properties
6.	Balance equations mass, energy and entropy of open, closed, stationary and in stationary systems
7.	Dissipation and exergy
8.	Selected idealized thermodynamic cycles: thermodynamic cycles, reversible processes, Rankine cycles, gas turbines, combined cycle gas turbines, combustion engines
9.	Mixtures of ideal gases, evaporation and condensation, humid air

The modeling approaches include the modeling of physical properties (using equations of state, model systems like the ideal gas or ideal liquid, and phase diagrams), the modeling of plant components (such as heat exchangers, turbines, pumps, compressors, throttles, etc.) used in technical processes, and thermodynamic processes (adiabatic, isothermal, isobaric, isentropic, etc.). Applications to technical processes, thermodynamic cycles and humid air processes combine all the previously listed individual subject matters.

Exam Design

After having decided on the learning objectives and subject matters, we follow Biggs' suggestion and focus on exam design and how we can identify the students' actual achievements and make those achievements visible.

The four midterm exams and the final examination (see Figure 6) have to align with the learning objectives and the learning activities in order to provide a high-quality learning environment. Obviously, we cannot test all the subject matter covered over the course of two semesters, but we attempt to test all four abstract learning objectives and a significant selection of the subject matter (see Table 2, Table 3, and Figure 4, respectively).

As depicted in Figure 5, the final exam consists of five separate testlets. The word *testlet* originates from educational theory.[15] It denotes a self-contained unit consisting of

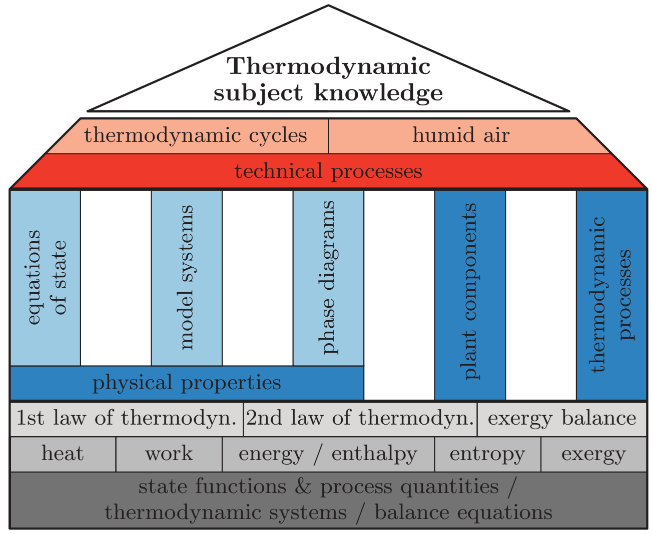

Figure 4. *Visualized thermodynamic subject matters covered in the course Engineering Thermodynamics 1/2. Thermodynamic fundamentals are located at the bottom, modeling approaches in the middle, and applications to engineering problems at the top.*

closely related exam tasks, often characterized by a shared problem statement or topic. A testlet may consist of several exam tasks or sub-tasks. While all four learning objectives (see Table 2) are tested in all testlets, the different subject matters covered in the course are split into individual testlets.

The first testlet consists of independent short exam tasks covering material from all subject matter that is not tested in the other four testlets. It tends to focus on factual knowledge and reproduction of basic facts or concepts. Testlets 2-4 are longer and include guided exercises with several thematically grouped exam tasks, where each exam task can be solved individually (by giving intermediate results if necessary). The second testlet mainly covers a short modeling problem with focus on the second law of thermodynamics (entropy production, entropy of mixtures of ideal gases or the like). Testlet number three is a more complex thermodynamic cycle (often a steam process), while the fourth testlet covers the subject matter humid air. The fifth testlet is an unguided problem without separation into individual exam tasks, in which the students are expected to solve a thermodynamic problem autonomously, without being guided by the structure of exam tasks. It is not fixed to a specific subject matter.

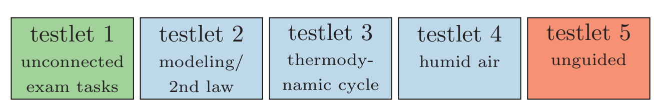

Figure 5. *Exam structure showing the five testlets (exercises that may consist of several sub-tasks) and their characteristics. The color coding intends to show similarity in structure.*

We strive to keep the testlets' problem specification as brief as possible and free of unnecessary information because we do not want to test for text comprehension or foster language difficulties for non-native speakers.

Description of Course Structure and Learning Opportunities

Further following the idea of *constructive alignment*, we finally have to review the lectures, exercises, and other components of our course on engineering thermodynamics. We limit the presentation to the basic learning opportunities during our one-year course. This reflects the basic set-up of lectures, exercises, guided tutorials, consultations, and exams.

As depicted in Figure 6, the course extends over two semesters and consists of plenary lectures, guided plenary exercises, and guided tutorials in groups of up to 25 students (under the supervision of student teaching assistants who have acquired a qualification for tutoring in engineering thermodynamics). Office hours with the teaching assistants and student teaching assistants are offered weekly during the semester and twice before the final exam. There is no graded homework.

Each semester there are two midterm exams; two out of four must be passed in order to participate in the final exam, which exclusively determines the final grade. All exams are "closed book," but the same formulary as used in the guided plenary exercises and guided tutorials is provided. The final exam is offered each semester, so that students who have not passed the exam have the opportunity to repeat it after roughly six months. The passing rate for each exam is usually around 60-70%, taking both initial and repeat exams into account.

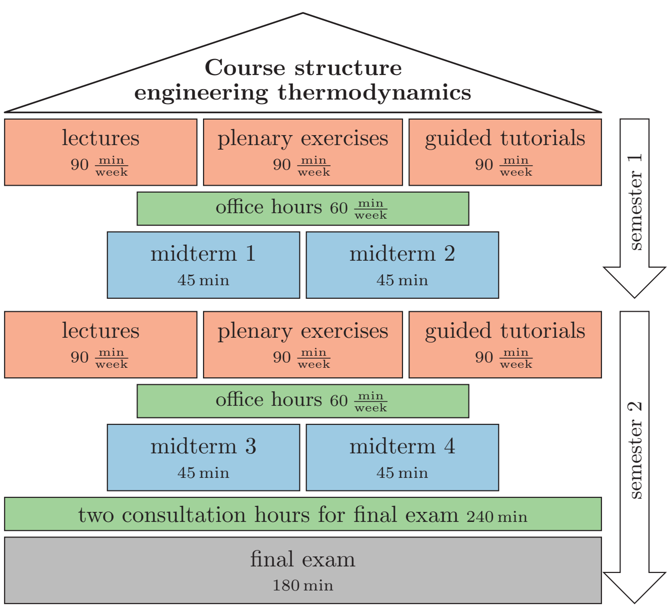

Figure 6. *Course structure showing the teaching elements for each semester for the two-semester course Engineering Thermodynamics 1/2 at the University of Stuttgart.*

The presented course structure is the result of the initial course planning as well as of several reviews and adjustments over the past years. In 2012 guided tutorials were introduced with the specific aim of resolving students' comprehension difficulties. They follow the concept of peer learning, which is practiced at many universities.

The following section discusses additional aspects of our course design that contribute significantly to the quality of the learning environment.

RESULTS FOR A QUALITY LEARNING ENVIRONMENT

In the previous section we have already outlined some measures that are fundamental to any supportive learning environment. In the following section we will build on these and focus our attention on two closely related aspects of student learning preferences: (1) test coping as surface level learning and (2) problem-solving strategies for a deep level understanding.

As mentioned in the introduction, we conducted a comprehensive survey on our students' study experience in 2014/15, followed by a closer monitoring of exam quality in subsequent years. The survey included a large number of qualitative data as open-ended survey questions on the learning process. In this way our students were able to express themselves freely on many study-related topics, such as learning preferences, study conditions, issues with the syllabus, and possible influences on study success. This reflects the main reason and objective behind our survey: we want to take the students' perspective on their study experience into account. The following insights draw heavily on the survey results, especially with regard to learning preferences and exam performance.

First, we present results from our qualitative data on learning preferences. This is complemented by insights into how students actually approach thermodynamic tasks. Both focus on test coping and learning strategies and are summarized hereafter. We then shift the perspective and discuss how we try to help students to achieve a deeper level of understanding. Problem-solving strategies are introduced and implemented on every level of our course. This is closely related to cognitive apprenticeship (Figure 9). Finally, we conclude with some remarks on exam quality and test fairness; both topics are discussed based on results of a statistical analysis of our exams over several years.

Students' Learning Preferences

Figure 7 shows answers of 431 students at the beginning of the course (first lecture) to the question: *What is your personal recipe for success, in order to prepare yourself for final exams in technical and mathematical study courses?* By far, the preferred learning activity is the repetitive work through available exercises and old exams. This attitude is quite stable. One year later, the same cohort of students (235 participated in the exam) were asked directly after the final exam: *Now that you just finished the final exam in engineering thermodynamics, what was most helpful for your exam preparation?* The result in Figure 8 is remarkably similar, especially since both questions were open-ended questions without any given options or suggestions.

The most striking result is the strong dominance of learning strategies concerned with tedious, repetitive solving of former exams and similar exercises. This comes with a general tendency towards surface approaches to learning, clearly visible in many of the students' answers. In particular the weak students use surface strategies for *plug and chug* solutions.[1] (pp. 299, 315) Of course, strong students with an advanced understanding of thermodynamic principles also have to rely on some kind of test wisdom. This is in line with our expectation and supports exam proficiency as an important competency from students' perspective as shown in Figure 1.

However, repetitive surface approaches to learning are not the only learning preferences. The two graphs also show that the guided tutorials, group learning, and self-study are important aspects of exam preparations and learning strategies. The personal importance increases over time. In hindsight, many students realize the importance and positive effects of guided tutorials, which are a genuine social learning environment. Also, the guided tutorials try to help students to achieve a deeper level of understanding by approaching exam tasks with thermodynamic principles in mind, not with plug and chug strategies for test coping. As a result, we greatly improved our efforts to support and encourage social learning *and* to explain to our students the difference between surface and deep level approaches one can use when learning for thermodynamics with old exams or exercises.

Furthermore, many students identified study and resource management as a crucial and often problematic part of their daily routine and exam preparation. In particular the students with good results on the exam describe that the subject of engineering thermodynamics was not the problem, but rather dealing with the study situation. Time pressure, complex arrangements of courses, and competing lectures or seminars are major obstacles that require additional abilities in resource-, study-, and self-management.[1] (pp. 295) We started to use the expression *conflicting learning priorities* to describe and identify the issues and raise the awareness

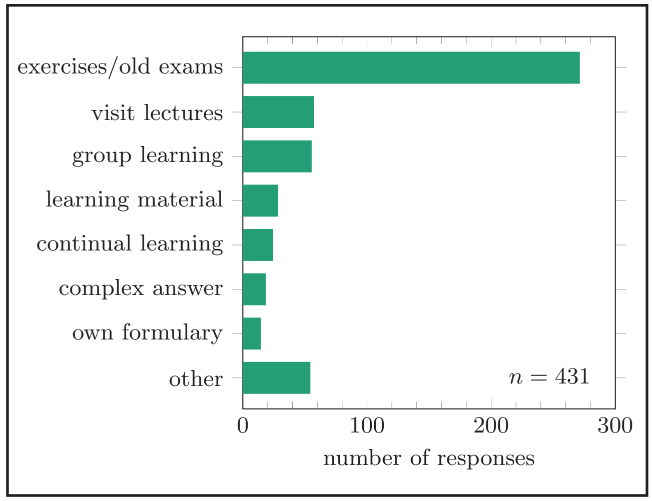

Figure 7. *Categorized survey answers to the open question "What is your personal recipe for success in order to prepare yourself for final exams in technical and mathematical study courses" from 431 students at the beginning of the course in the first lecture of the winter semester 2014/2015. Multiple responses were possible.*

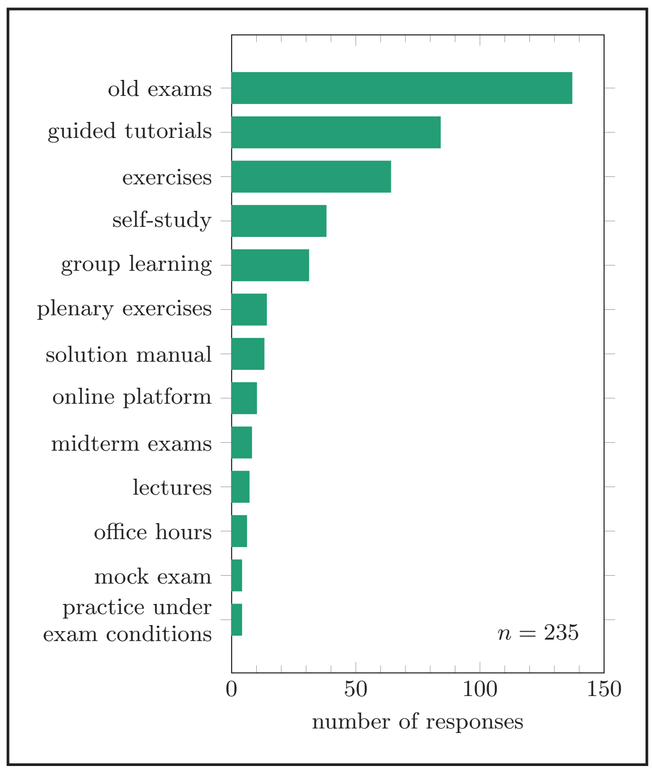

Figure 8. *Categorized survey answers to the open question "Now that you just finished the final exam on engineering thermodynamics, what was most helpful for your exam preparation" from 235 students just after finishing the final exam in the summer semester 2015. Multiple responses were possible.*

of the aspect among students and faculty staff. Making the problem visible is a necessary first step, and we found that insufficient attention was being paid to this crucial aspect of students' experience of the learning environment.

Finally, our results also show that successful exam preparation is ultimately achieved through self-study and individual engagement with learning materials and exercises. Knowing how to use learning material in order to avoid surface approaches to learning and to achieve deep level understanding is a crucial point in this respect. The following sections will discuss this aspect in more detail.

The survey results, especially the qualitative data from the many open-ended questions, support the inclusion of several aspects to the competency model we introduced with Figure 1. Putting exam proficiency as well as social and personal competency into the model increases visibility for students and staff alike and raises awareness on the complex reality of the study experience. Visibility and awareness are the first important steps in order to implement additional means for the improvement of the learning environment and the course design.

The following section will further detail how students in our course actually approach thermodynamic problems, especially in an exam situation.

Students' Approach to Exam Tasks

In Figure 1 we included exam proficiency as an important competency for students in order to tackle our course. This is not necessarily a desirable thing. We want our students to learn for the professional competencies and its application beyond the exam situation. However, we have to understand how students actually prepare for and face the exam situation in order to improve our learning environment and offer better support.

As soon as we look more closely at the students' approach to learning and how they deal with the exam, we see a substantial discrepancy. There are some students who focus on conceptual understanding and the application of knowledge to solve thermodynamic problems. Many others tend to focus on solving the exam as a mere formal challenge.[1] (p. 298) This observation has been made frequently in educational research. It is usually described as a *conceptual* or *deep level* versus *surface approach to learning*.[13,16] The latter is characterized by students' strong orientation towards dealing with exams in a superficial – but possibly effective – way. But *how exactly* do students approach the exam tasks?

From the students' responses in our survey, we were able to better understand this crucial aspect. We identified a set of important steps that students use as a reliable strategy during the exam situation. The following list shows how students describe their experiences with the exam situation and typical actions for dealing with exam tasks:[1] (p. 225)

1. Anticipation of the unknown; the exam confronts with a new task and new subject matter. (The task and subject matter were covered in the course but feel new.)
2. Discern the general type of exam task and relate it to typical solutions. Identify "troublesome" aspects of the exam task.
3. Estimate the difficulty of the exam task and the time necessary to complete it. This includes a comparison of the exam task at hand to those known from past exercises and exams.
4. Identify a good modeling approach and a possible scheme for effective solution of the exam task.
5. Identify necessary steps towards a solution; recognize good approaches. Identify missing variables and given information; *identify the pieces of the puzzle* or *convert the text to a thermodynamic picture*.
6. Identify implicit assumptions and use them properly; *what variables can be dropped,* are there *hidden clues* or *random assumptions?*
7. Identify the critical aspects of the exam task: variables or values that must be calculated, ambiguous data, errors or inconsistencies, or crucial steps toward the final solution (bottlenecks).
8. Maintain focus and concentration. Avoid careless mistakes.
9. Combine and rearrange equations.
10. Calculate quickly! Perform with routine and efficiency, if possible.
11. Do not get lost in details or minor aspects.
12. Organize your desk, the exam sheets, formulary, and additional materials.
13. Do not only respond mechanically, try to understand the thermodynamic problem.

Interestingly, this list shows perfectly that the students' perception of the exam situation does comprise very different aspects that are perceived as a single, holistic situation. It includes aspects of time and stress management, anticipation of the unknown, *plug and chug* strategies, emotional control and focus, desk management, and so forth. The list also shows that conceptual understanding plays a very inferior role.

Problematic Learning Strategies

In the previous sections we identified two major issues with our students' approach to learning. The survey responses show that repetitive learning strategies based on old exams or similar exercises are very dominant among students. Additionally, a detailed look into how students' approach and assess a given exam task reveals a complex mix of different aspects, among which conceptual understanding and a deep level approach plays only a comparatively small role. Only items 5 and 13 in the list given in the previous section seem to embrace conceptual understanding. All others aim at efficient test coping. Consequently, we have to accept that students do not only use thermodynamic knowledge and concepts to prepare for and solve the exam. They also develop and train to cope with the exam as a specific, problematic situation. This is usually called *coping/dealing with the test* and is an important dimension of competency from the students' perspective, even though it is usually not considered desirable by the teachers.

While we acknowledge the students' perspective in our competency model as presented in Figure 1, which does include exam proficiency as an important aspect, we also want to facilitate a strong professional competency built on conceptual understanding and deep level learning strategies. Test coping becomes a problem when it dominates students' learning activities. In this case repetition and *dealing with the test* replace conceptual understanding. This is a major problem not only in engineering thermodynamics, but also in other engineering courses. What does that mean for a supportive learning environment? The challenge is to make sure that good strategies for deep level learning are visible and integrated throughout all these diverse aspects of the study situation. The gap between (necessary) surface approaches for the exam situation and a deep conceptual understanding must become narrower. For example, repetitive solving of old exams in solitary self-study is not a bad learning preference on its own, unless it fails to include good learning strategies that aim for a deeper understanding and avoid surface approaches to learning.

In the following sections we offer some examples of how we approached this problem. First, we introduce a thermodynamic problem-solving strategy based on conceptual understanding. This is followed by its implementation with help of *cognitive apprenticeship* in order to make sure that conceptual understanding is a viable option for students with very different learning preferences. Finally, we conclude the results with some thoughts on exam design and analysis, since the exam is the final and definitive measurement for the achieved competency. It has to be of such a quality and design that it makes deep level understanding a visible and rewarding approach.

Subject-Specific Problem Solving

The idea is straightforward: students first need a clear and applicable understanding of a thermodynamic problem-solving strategy, one that allows for an almost universal application to different engineering thermodynamic problems. In a second step the learning environment has to transport and promote this strategy in every aspect in order to allow students with very different learning preferences to understand and benefit from this strategy.

With regard to the first point, we introduce a guideline for *subject-specific problem solving* in our course on engineering thermodynamics on all levels. It represents an approach to thermodynamic tasks based on conceptual understanding and is therefore an integral part of the professional competency as depicted in Figure 1.

In order to successfully solve engineering thermodynamic problems in alignment with the learning objectives, we propose to the students the guideline and solution strategies shown in Table 4. Almost all challenging problems that stu-

TABLE 4
Subject-specific problem solving in engineering thermodynamics and solution strategies.

General Approach
1. Prepare process flow and/or required physical property diagrams of the problem. • Define and draw balance domain (system boundary). • Sketch all incoming and outgoing mass and energy flow rates. 2. Formulate balance equations (mass balance, first and second law of thermodynamics, exergy balance) in extensive quantities. • Simplify balance equations according to the problem specifications; apply simplifications. • Always construct balance equations starting from the supplied formulary. 3. Application of physical property model to balance equations, possibly by using given information. 4. Rearrange equations explicit in the desired variable, no numerical values should be used until the desired value is calculated to avoid conversion errors.
Solution Strategies
If the mass flow rate or an extensive state function or process quantity is sought after, start with the process step including an extensive property. Use a table in which all state functions are added for each process step; some state functions remain constant in certain steps. In humid air problems, quantities are expressed relative to the mass flow rate of dry air, which usually remains constant. Exergy loss can be calculated in two ways: via an exergy balance or through entropy production. Work is often easier calculated using the first law of thermodynamics than by integrating the pressure of a thermodynamic process.

dents encounter during our course on engineering thermodynamics can be approached and solved with this guideline in mind. Basically, it suggests that students translate a given physical-technical problem into thermodynamic principles and a solvable mathematical representation that translates back to a technical or physical answer to the given problem.

The important thing with regard to the learning environment is that these guidelines and strategies offer a *reliable* way to approach any problem within the scope of our course. It is more flexible and efficient than *plug and chug* strategies and certainly more rewarding when it comes to deep level understanding than repetitive strategies of surface learning. The challenge is how these principles can be successfully conveyed to a diverse group of students with different learning strategies and preferences.

Cognitive Apprenticeship

In order to promote *subject-specific problem solving* based on conceptual understanding in all aspects of our course and for students with different learning preferences, we rely on *cognitive apprenticeship* as a helpful method. Cognitive apprenticeship is an approach to teaching and learning in terms of a master-apprentice relationship. The method of cognitive apprenticeship is designed to reveal the teacher's *inner communication* and implicit thought processes or applied knowledge.[17] Students learn in the context of "realistic" problems and close to a deeper conceptual understanding of the underlying principles.

The guideline and strategies given in Table 4 represent the underlying principles of our cognitive apprenticeship design throughout the whole course. Following the idea of *constructive alignment*, they are instructive for our lecture, plenary exercises, guided tutorials, exam design, and additional learning materials. The implementation of cognitive apprenticeship for our course is depicted in Figure 9. The three central aspects of our learning environment – lecture, exercise, tutorials – represent the important steps of cognitive apprenticeship, albeit on a larger, weekly scale, rather than within one 90-minute learning sequence.

In the plenary lectures the covered material is derived, discussed, and clarified with examples or experiments. The focus rests on relational aspects of the topics at large. Connections are made, and the subject is presented as a whole,

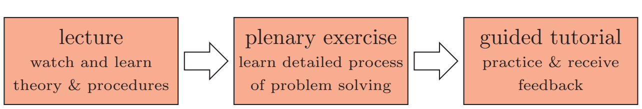

Figure 9. *Implementation of cognitive apprenticeship in the course Engineering Thermodynamics 1/2 covering the various teaching elements; with each step the level of engagement is increased gradually.*

together with its relevance and role within the syllabus and with regard to the learning objectives. The plenary lecture tries to grasp and convey theories and procedures in one sketch and by example.

During the guided plenary exercises, the same material is applied by the teaching assistants to previously distributed problems, leaving enough time for questions. The focus here is on revealing implicit thought processes in the context of a thermodynamic problem to teach the students the competencies required in the exam. In plenary exercises cognitive apprenticeship means that the teacher not merely develops solutions to exercises, but reveals the *inner communication* that leads to a solution approach and relates it to the defined learning objectives.

The same principles are applied in the guided tutorials, where the students increasingly apply their newly acquired skills independently to thermodynamic problems, with student teaching assistants supporting learners when help is needed (instructional scaffolding).

With each step, students have to apply a higher order of cognitive activities and levels of engagement, which is designed to activate the more passive students to achieve the learning objectives and deep-level understanding. At the same time, we respond to the observation that different students prefer different learning styles and settings. The conceptual approach to *subject-specific problem solving* flows through the lecture as well as through the exercises and tutorials, thus giving students multiple chances to "board the train" from their preferred learning situation (including learning material for self-study).

By proposing a universal, conceptual guideline for the solution of thermodynamic problems within our course (Table 4) and by making this the underlying principle of a cognitive apprentice design, we create a learning environment that supports conceptual understanding in all its aspects. This aims at reassuring our students that the conceptual, deep level approach to exam tasks and exam preparation outclasses superficial alternatives.

However, from the student perspective, investment and benefit have to be weighed against each other. Is the conceptual approach really worth the effort? We slightly shift this question and come to ask ourselves: does our exam design reflect and reward conceptual approaches in a sufficient way?

Exam Quality and Test Fairness

The exam has to reflect the intended learning outcomes as well as the learning activities encouraged by the course design. After the implementation of *constructive alignment* and *subject-specific problem solving*, in combination with cognitive apprenticeship, a critical review of our exam design was in order. Our basic exam design is outlined around Figure 5. In the following section, we add two additional major aspects. They are the result of a four year-long monitoring of our exams, including statistical analysis based on item response theory modeling. The details of this analysis are presented in a dedicated paper (see Braun et al.[3]).

First, after all the changes to our course design, we felt that our grading process should reflect *constructive alignment* and the importance and transparency of deep level understanding we promote through all our learning opportunities.

We apply the following grading structure for final and midterm exams, whereby points for the thermodynamic modeling approach (AP) and points for the actual quantitative solution (SP) are counted separately in accordance with *subject-specific problem solving* and the advocated partial credit model analyzed in section II in Braun et al.[3]

- Correct application and simplification of first or second law of thermodynamics (AP)
- Correct application of physical property model (AP)
- Correct rearranged equation for calculation of desired variable (SP)
- Calculating or taking correct value from table; may include interpolation (SP)
- Correct numerical value calculated (SP)

What sounds like a simple step required a thorough review of the exam design process. As a result, the transparency regarding the importance of thermodynamic concepts is greatly increased. Students can rely on the fact that finding the right approach and showing conceptual understanding warrant a proper recognition and reward. Also, the grading system improves the exam design process, since required modeling approaches for the exam tasks are explicitly reflected and made transparent.

A second result of the exam analysis was a general increase in exam quality and test fairness. This was largely due to the revised grading process. It allowed for a partial credit model to be fit to the students' responses with a high degree of model fit. This offered a mathematical tool to analyze our exam for a latent competency structure and the degree of test fairness (in regard to whether our grading process actually reflects the students' empirical ability as measured by the partial credit model). For more details, see Braun et al.[3]

CONCLUSION

We started from a simple yet demanding question: *How can we improve our learning environment and, subsequently, the quality of our learning outcomes?* We chose to answer this question by example, using our course on engineering thermodynamics as a case study. An extensive survey on learning experience and a statistical analysis of our exam results form the foundation on which we built our evaluation process. We encourage faculty to undertake regular surveys with focus on learning experience and students' perspective of the study situation. There already exist several established low-scale methods, like *classroom assessment techniques* or *teaching analysis poll*. With a relatively small effort, such surveys yield invaluable insights into a constantly changing study reality.

For our improvement process we found that one major step was the acknowledgment of how students actually learn and deal with their study situation as a whole, not only with regard to the exam, or the lecture, or some other aspect of the learning environment. Our survey revealed many aspects about how students perceive and tackle our course within the framework of their study situation (leading to the competency model we propose in Figure 1). The dominant tendency towards surface approaches to learning was a major issue. So we initiated a process to strengthen conceptual understanding and *subject-specific problem solving* that aims for deep level understanding.

The rearrangement and alignment of all parts of our course under the directive of a subject-specific yet very powerful problem-solving strategy was the first major step. Cognitive apprenticeship offered important inspirations to guide our students through different steps of increased cognitive complexity and conceptual understanding. Also, by making *subject-specific problem solving* a universal reference in all parts of our course, we could better address different learning preferences among our students.

Furthermore, the whole review of our learning environment also contributed to the exam design process. In return, a careful investigation into our exam's quality and fairness informed us about necessary improvements to our test design and grading procedure. We believe that our approach and many results are comparable and applicable to courses similar to our own and we hope readers find helpful inspiration for their own reflection on their learning environments and possible improvements thereof.

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