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Knowledge stratification to enhance assessment practices

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Abstract

This paper is a conceptual paper exploring knowledge stratification. Designing assessment tasks to adequately test what has been taught and to meet the learning objectives of a course is a non-trivial task. In the light of Generative AI it has become even more challenging. Whilst much ink has been spilled on the issue of assessment tasks being outsourced to LLMs the issue that is more pertinent to engineering education is establishing what needs to be taught to ensure best engineering practice. To this end developing a course specific knowledge stratification framework or epistemic framework may be helpful.

In this paper, the use of Blackie's epistemic assessment framework will be demonstrated using mass-energy balances as an example. The implementation of the framework to facilitate the adaptation of existing assessment tasks and the necessitation of the development of new assessment tasks will be discussed. This framework which distinguishes between 'discipline specific vocabulary', 'procedural knowledge', 'conceptual knowledge' and 'powerful knowledge'. The framework may need augmentation or adaptation for each specific course but provides a useful starting point for knowledge stratification. The balance in the kinds of knowledge required as the use of AI tools and AI agents becomes more common place in engineering practice is likely to change. This framework gives a foundation from which strategic decisions can be made to make such changes.

Introduction

This paper is a conceptual paper which outlines the use of the epistemic assessment framework using mass-energy balance as an example. The fact that performing a calculation does not imply understanding the underlying concept has been well demonstrated. One of the most highly cited and memorable examples is the work of Mazur and colleagues [1, 2] who demonstrated that pre-med students in a physics class at Harvard could perform highly complex mathematical procedures but did not have a good grasp of the real world meaning of physical phenomena these mathematical manipulations were describing. Blackie [3] has noted a similar problem in organic chemistry proposing that in many tests and exams procedural competence is taken as a proxy for conceptual understanding. For example, in general chemistry assessments the ability to balance a chemical equation is routinely tested. This is presumed to mean that students understand that underlying principle of conservation of matter, but this underlying principle is rarely probed.

Why is this important?

The first student outcome required by ABET for accreditation of engineering programs is 'an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science and mathematics'[4]. The question worth asking is whether sufficient attention is given to the second half of that statement – the capacity to apply principles. Without a good grasp of the principles the sixth student outcome ‘an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions’[4] is not likely to be within the students grasp.

In their longitudinal study of chemistry and chemical engineering students Ashwin et al make an argument for the development of an ‘inside view of knowledge’ as the value proposition for higher education[5]. They also note that not all students who graduate have developed this inside view of knowledge. This study takes a phenomenographic approach and has not interrogated the mechanisms through which this inside view of knowledge can be developed. However, it is hard to imagine how one might develop that inside view of knowledge without a robust grasp of the principles. As suggested in the opening paragraph of this paper, we cannot assume that students are seeing the underlying principles we intend to teach unless we are assessing their understanding of those principles.

In this paper, the epistemic assessment framework is presented as one approach to ensure that underlying principles are tested using mass-energy balance as an example. The contribution of this paper is to show that the epistemic assessment framework developed by Blackie for organic chemistry [3] can be meaningfully adapted for engineering courses.

Epistemic assessment framework

The origin of the framework is inspired by Legitimation Code Theory. LCT provides a suite of tools which can be used to analyze knowledge practices[6]. Each tool offers a pair of associated but independently variable dimensions. The purpose is to make the complexity of the knowledge practice more visible. In a similar fashion, Blackie [3] used ‘knowing how’ and ‘knowing why’ as the two axes to develop the epistemic assessment framework (Figure 1).

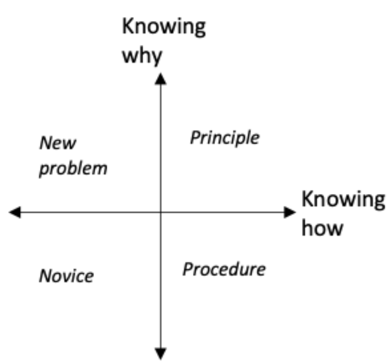

Figure 1: Relationship between different problem solving capacities related to knowing how and knowing why

The student at the beginning of a new course begins in the novice quadrant (Figure 1) and progresses to the procedural quadrant as they master various operations, acquiring procedural knowledge about how to perform tasks. True understanding emerges when learners grasp not just the mechanics but the underlying principles and reasons behind these operations, marking their transition to the principle quadrant where conceptual understanding deepens. Experts and specialists can then apply this knowledge flexibly in novel situations, drawing on strong conceptual foundations while adapting existing procedures or creating new ones to address unforeseen problems. In rare cases, an individual may experience an intuitive breakthrough—a genuinely original insight that opens an entirely new fields of inquiry, effectively returning them to the novice quadrant in this new domain where procedural protocols have yet to be established. This final creative leap lies beyond what most undergraduates will achieve and cannot reasonably be assessed through conventional examination, educators should recognize and credit such innovation when it occurs, even though it typically transcends the scope of any single course. Thus, the primary aim of teaching knowledge-based subjects, such as mass-energy balance, remains focused: to convey a well-defined set of principles along with their corresponding procedures.

Blackie used the understanding implied in Figure 1 as a foundation for the epistemic assessment framework. In the framework the four quadrants are translated into types of knowledge (Table 1)[7]. In her work the focus was on organic chemistry, but here the example questions are taken from the curriculum of a mass-energy balance course.

Table1: Epistemic assessment framework exemplified for a mass-energy balance course

Category	Example Questions	Quadrant	Knowledge Type
Vocabulary	Define terms identify symbols recognize units	Novice	Knowing the fact
Simple Procedure	Single-step calculations Unit conversions Direct formula application Reading property tables	Procedural	Knowing how
Complex Procedure	Multi-step material balance Energy balance with phase change Simultaneous equation solving Known reactor problems Complete analysis of standard configurations	Procedural	Knowing how
Principle	Explain why mass/energy must balance Apply conservation laws to new situation Justify term simplifications Explain physical meaning of equations Troubleshoot balance discrepancies	Principle	Knowing why
New Problem	Novel process configurations Design measurement strategy Develop solution approach for unfamiliar systems Integrate multiple unit operations not seen together before	Problem	Powerful knowledge

Some information just needs to be learnt and constitutes the ‘vocabulary’ of the course. These items could, in principle, be learnt entirely separately from the course. They have little meaning on their own, but if they are learnt, they lower the cognitive burden of the student and make following lecture content easier. These vocabulary items can be listed and tested early on in the course. A closed book, invigilated test is an appropriate form of testing the vocabulary.

Simple and complex procedures are quite often the focus of teaching on mass-energy balance courses. This is because it is vitally important that the students learn to solve these kinds of problems. This is ‘knowing how’.

Principle questions are focused on ‘knowing why’. Given the pedagogical focus on the procedural knowledge of solving these problems, it is entirely possible that this level of question is not directly tested.

New problems require the application of the underlying principles to new situations. This level of question may well be beyond the scope of the desirable outcomes of a particular course, but if the student is to gain the capability of multi-dimensional engineering design, they may well need to draw on these principles in unexpected guises.

In reviewing a set of mid-terms and exams from one mass-energy balance course at an R1 institution it was apparent that all questions fell into the category of complex procedure. Given the importance of solving such problems a strong weighting towards complex procedures is to be expected. However, the epistemic assessment framework makes visible the fact that one cannot take such procedural knowledge as a proxy for grasping the underlying principles. And as has been discussed above, the development of the ‘inside view of knowledge’ is likely to require the embodiment of the underlying principles.

How does this work in practice?

Consider a question which could be asked on a mid-term or exam for a mass-energy balance class.

"A steam turbine operates under the following conditions:

- Inlet: Steam at 5 MPa, 400°C, 50 kg/s
- Outlet: Steam at 10 kPa, quality = 0.95
- Heat loss from turbine: 100 kW

Calculate the power output of the turbine."

At the vocabulary level, students need familiarity with standard pressure units (MPa, kPa) and temperature measurements (°C), along with specialized terminology such as "quality," which denotes the vapor fraction in a two-phase mixture. Additionally, they must recognize that power output represents the work performed by the system. These definitional requirements form the basis for subsequent analysis but remain distinct from deeper conceptual engagement.

Beyond terminology, students require low-level conceptual frameworks to approach thermodynamic problems systematically. This includes identifying the problem type—in this case, an energy balance on an open system—and selecting appropriate analytical tools such as steam tables for determining enthalpy values. Recognition that the process operates under steady-state, steady-flow conditions further guides the analytical approach. These conceptual stepping stones enable students to organize their problem-solving strategy without yet demanding sophisticated intuition for the physical system. Students may also learn to match problem type to approach through engaging with multiple examples and cannot be presumed to have acquired the capacity to explain why they are choosing the procedure they are.

The procedural dimension of thermodynamic problem-solving involves executing a series of technical steps with precision. Students must navigate steam tables to extract the inlet enthalpy (h_1) for superheated steam at specified conditions (5 MPa, 400°C), then determine the outlet enthalpy (h_2) using the relationship $h_2 = hf + x \cdot hfg$ with values obtained at the exit pressure (10 kPa). The final calculation applies the work equation $\dot{W} = \dot{m}(h_1 - h_2) - \dot{Q}loss$ to determine numerical power output. While these procedures are essential for obtaining correct answers, their successful execution does not necessarily demonstrate understanding of the underlying physical principles governing turbine operation.

True principle-level understanding transcends procedural competence and engages with the physical meaning of thermodynamic relationships. This includes comprehending why the first law mandates energy balance, recognizing the physical mechanisms by which heat loss diminishes power output, and understanding the actual thermodynamic processes occurring within the turbine. Students working at this level also recognize when simplifying assumptions—such as negligible kinetic and potential energy changes—are appropriate and understand their physical justification. Conventional calculation problems often fail to assess this deeper understanding, as students can arrive at correct numerical answers through algorithmic application of formulas without grasping the physical phenomena these equations represent.

To effectively probe principle-level understanding, assessment design must shift from calculation-focused questions to scenario-based inquiries that require physical reasoning. A modification of the problem might read:

"A steam turbine is performing below expected power output. Measurements show:

- Expected power: 50 MW
- Actual power: 45 MW
- Measured heat loss: 100 kW (as designed)
- Inlet and outlet conditions match design specifications

What physical phenomena might explain this discrepancy? For each possibility, explain how it would affect the energy balance and what additional measurements you would take to verify."

Rather than requesting a numerical calculation, this question asks students to propose physical phenomena that might explain the discrepancy, articulate how each possibility would manifest in the energy balance, and suggest targeted measurements for verification. This approach demands that students understand what the energy balance represents in physical terms, recognize how non-ideal behavior affects turbine performance, and establish connections between measurable thermodynamic properties and actual process behavior—competencies that remain inaccessible through traditional computational problems.

It is important to note that it is still essential to ensure that students are developing the required procedural competence. Thus, questions that actually test at the level of principle should not dominate. But the fact they are asked will require students to attempt to understand the material at the level of principle.

What is the impact?

Use of the epistemic assessment framework has only been studied to date in organic chemistry courses. Blackie et al [8] report that they used to code all questions on tests and exams in a manner that was visible to the students at the time of writing the assessment. Many students simply used the coding pragmatically to assist with time management. But some students reported finding the system helpful in developing their understanding of the subject. One student reported that knowing that they needed to look for the principle had changed how they studied in other disciplines too. In the same study, they note that pedagogical practices are also impacted as more care is taken to connect the procedural examples to the key principles.

There is, to date, no reported study of the efficacy of the epistemic assessment framework and students' capacity to transfer principles between courses. There is also no reported study on the connection between teaching principles more explicitly and the development of the 'inside view of knowledge'. There is thus plenty of scope for research into the use of the epistemic assessment framework.

How to use the epistemic assessment framework

Take an exam from your class and delineate what the student needs to know to answer each question. There may be several components required such as the use of notation (vocabulary); the employment of the correct formula; and there may be interpretation of the result. As you go through the exam, presume the path of least understanding is taken. For example, if the choice of formula could be ascertained through repetition of multiple similar questions, then a student relying on pattern recognition could accurately make the choice of formula. The student does not need to connect the formula with the correct law or understand the underlying principle. Once you have assigned the lowest understanding to all questions consider whether what the hypothetical student who takes that path might actually understand. If this level of understanding is acceptable in terms of your learning outcomes, the exam is adequate for the course. If the student is able to pass this exam without demonstrating evidence of grasping the underlying principles, consider where else in the course this is evaluated. If it is not evaluated, you need to redesign your assessments to ensure that the underlying principles are required. It will also assist the cognitive load of your students if you introduce some kind of vocabulary test. It is best to give a vocabulary list if you are going to introduce such a test.

In a time of Generative AI

The use of generative AI is beginning to permeate the daily practice of professional engineers. Whilst much of the research is still focused on software engineering, there are increasing numbers of papers focused on other forms of engineering. Rane reports on the ways in which ChatGPT can be used to analyse extensive datasets and simulate intricate structures in structural engineering [9]. Channi et al show ways in which generative AI are shaping engineering design for small products [10]. Srinivasan et al focus on process systems engineering at all scales from molecular development to supply chains [11]. There is little doubt that capacity to employ generative AI and the agents build from generative AI will be a required capability of engineering graduates. However, the way in which to meaningfully incorporate generative AI tools into undergraduate education is still under development. It is important to ask how these tools can be used to augment learning rather than bypass learning. To this end having a clear grasp of the distinction between vocabulary, procedural knowledge and principled knowledge will be useful. Thus the practice of using the epistemic assessment framework will assist instructors in making choices around how to employ different assessment tasks. Students do need to know a certain basic vocabulary to instruct AI tools correctly. Likewise they need to understand the logic and mechanics of calculations in order to be able to critically evaluate any numerical answer. This means that accurate utilization of generative AI requires a minimum intellectual grasp of the knowledge. The epistemic assessment framework can assist in making more visible what needs to be known. The student must grasp the underlying principles or the use of the AI tool cannot be guaranteed to be appropriate.

Conclusion

In this paper, the use of the epistemic assessment framework in engineering education has been demonstrated using mass-energy balance as an example. The argument has been presented that the use of this framework can assist in ensuring that the principles are tested and some evidence has been presented that in the context of organic chemistry that this has been helpful to students in mastering the subject. It has been suggested that the development of an 'inside view of knowledge' may be facilitated by ensuring that the students are more aware of the principles underpinning the course.

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