Laboratories-first optics and photonics education: analyzing epistemic insights in an educational program

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ABSTRACT

Optics and photonics education prepares students for careers in specialized fields, not only through theoretical knowledge, but also by developing practical skills and problem-solving abilities. Laboratory-based learning is widely accepted as a crucial component of physics and engineering education. However, is a year of labs effective as the first introduction to the field as done at the Laser Research Institute, Stellenbosch University? Students are introduced to optics and photonics through experimental laboratory work for a year before starting with the theory modules, covering optics, nonlinear optics, quantum optics, lasers, and spectroscopy.

This paper demonstrates the use of an analytical instrument based on the Specialization dimension of Legitimation Code Theory[1]. This instrument distinguishes different *epistemic insights* required of practitioners in a specialized field including principle-based knowledge (*purist insight*), practices legitimized by accepted procedures (*doctrinal insight*), the ability to think out of the procedural box to envision different possible approaches to a specialized problem (*situational insight*). The ability to transition in an appropriate way between insights has been shown to be crucial for problem solving in engineering. We use it to analyze our undergraduate program focusing on the role of labs. Results show that labs can give students practice in moving between *purist*, *doctrinal* and *situational insights*, thus preparing them for their capstone projects and future postgraduate or working environments. Feedback from recent graduates evaluates the efficacy. The analytical instrument has potential for application in optics and photonics curriculum design to prepare students for the diverse challenges in their future careers.

Keywords: curriculum design, laboratory-based learning, problem solving approaches, Legitimation Code Theory, Specialization

1. INTRODUCTION

Undergraduate optics and photonics education prepares graduates for both specialized postgraduate and industrial research and for careers in engineering environments. Problem solving skills in complex contexts, by drawing on fundamental knowledge, technical and computational skills, and situational insight are expected from graduates.

The Laser Research Institute at Stellenbosch University offers an undergraduate and Honors program in optics and photonics. The program structure is unconventional as students are introduced to optics and photonics by means of a year-long module in experimental laboratory work before starting with specialized theory modules. Graduates are successful in undertaking subsequent PhD studies and finding employment in industry in South Africa and abroad. An upcoming curriculum renewal process serves as motivation to analyze and evaluate the strengths and weaknesses of the program, including the impact of the labs-first structure.

An analytical approach from the theoretical framework of Legitimation Code Theory[1,2] (LCT) was chosen for this study. Building on the work of Bernstein[3], LCT offers a multi-dimensional set of analytical tools to evaluate, compare and visualize knowledge structures in educational practices. It is accessible to scientists and engineers, as the tools are experienced as “science-like” and flexible[4]. The Specialization dimension of LCT allows a focus on *epistemic* relations, which highlights that scientific practice is legitimated by *what* is studied and by *how* it is studied, where both may be specialized to a varying degree. Epistemic relations are used to distinguish different insights (“ways of thinking”) essential in science and engineering. The ability of students to transition between these insights is important for their studies, but even more critical for success in their careers[5].

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The epistemic relations of LCT Specialization have been used in engineering education to study problem solving practice in industry[5-7], inform curriculum reform[8,9] to prepare students better for engineering careers[10]. Optics and photonics education poses similar challenges in terms of preparing students for the workplace, therefore this study will draw on relevant conclusions from engineering.

This study demonstrates how the analytical instrument offered by *epistemic* relations of LCT is adapted to analyze the BSc and BSc Honors program at Stellenbosch University and what understanding can be gained with regards to strengths and weaknesses of the program. The focus is to investigate how the 3rd year laboratory module, serving as the first introduction to optics and photonics, contributes to preparing our students for their further studies and careers. These results will inform future curriculum development.

2. THEORETICAL FRAMEWORK

Legitimation Code Theory[1,2] builds on Bernstein's concepts of knowledge structures[3]. Knowledge of different disciplines is organized into inherently different structures, for example a hierarchical knowledge structure where theories build on and integrate one another as in Physics and a strong horizontal knowledge structure that "consists of a series of specialized languages"[4] as in Mathematics.

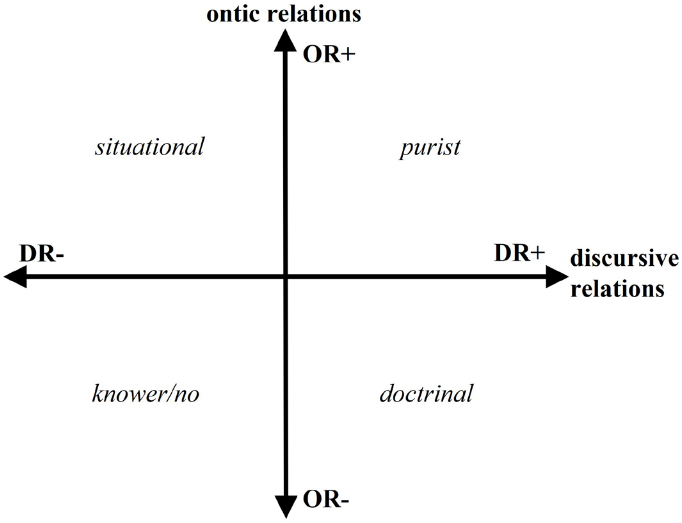

Figure 1. The epistemic plane[2].

Legitimation Code Theory extends this conceptualization and offers conceptual instruments for more detailed analysis of knowledge practices. In the Specialization dimension of LCT the focus is on what legitimizes knowledge practices in a specialized disciplinary field. In Physics *epistemic relations* - specialized knowledge, skills, or procedures - are the basis for legitimation. *Epistemic relations* highlights that "practices may be specialized by both what they relate to and how they so relate"[1]. This relationship is visualized on a Cartesian plane, called the *epistemic plane*, as illustrated in Figure 1. The vertical axis displays *ontic relations* ("what"). The relative scale shows how strongly the object of study is bounded to legitimately recognized concepts in the field of specialization. For example, "diffraction" is a legitimate specialized concept in optics, thus showing *stronger ontic relations* (OR+). The concept "signal-to-noise ratio" is frequently used in optics but is a general concept, not strongly bound to the specialized field of optics and therefore, in this context, displays weaker *ontic relations* (OR-). The horizontal axis represents a relative scale of *discursive relations* ("how") – showing how strongly the method or approach of the study is bounded to a recognized procedure or approach in the field of specialization. For example, Maxwell's equations are derived by a legitimate specialized approach, therefore having stronger *discursive relations* (DR+), whereas the task to reduce the frequency drift of a laser can be approached in different ways depending on the situation thus showing weaker *discursive relations* (DR-).

The four quadrants are interpreted as different *insights*, or ways of thinking. *Purist insight* (top right, OR+, DR+) consists of knowledge practices where both the object and the procedures are important for legitimacy. Physics principles and laws as traditionally taught are in this quadrant. *Doctrinal insight* (bottom right, OR+, DR-) is appropriate when it is important to apply a recognized procedure or methodology to whatever the object is. *Situational insight* (top left, OR-, DR+) is required when the object of study is legitimately recognized in the field, but there are many possibilities in how to approach the study and what methods to use. *No/knower insight* (lower left quadrant, OR-, DR-) refers to practices involving general (rather than specialized) objects and methods, or where social relations play a significant role.

3. ANALYSIS RESULTS

The program consists of a three-year BSc degree followed by a one-year BSc Honors degree. During the first 2 years a general introductory physics curriculum is taught in parallel to mathematics and other electives. In the third year (final year BSc) students have two major subjects. The 3rd year physics major includes theory related to electromagnetic waves and basic optics (10% of the physics credits) and the year-long laboratory work module (25% of the physics credits) that we use to introduce the students to optics and photonics experiments. The 4th year (Honors) curriculum consists of 100% physics including approximately 40% optics and photonics theory modules (optics, nonlinear optics, quantum optics, lasers, spectroscopy) and experimental research project weighted 32%. Notably students are introduced to optics and photonics through experimental laboratory work, a full year before they start with specialized theory modules in the field. The unconventional structure is necessitated by a diverse student body and the requirement to deliver graduates with a wide scientific basis on 3rd year level.

The *epistemic relations* in the 3rd year laboratory module and representative 4th year optics and photonics theory modules were analyzed. The criteria for placing a learning activity into a specific quadrant was based on the *student's perspective* – whether the learning activity requires the *student* to engage in *purist*, *doctrinal*, *situational*, or *no/knower* insight.

In Figure 2 the occurrence of the different *insights* and *insight shifts* in the 3rd year laboratory module and a representative 4th year theory module (on nonlinear optics) are represented semi-quantitatively on the *epistemic plane*. In the 4th year theory module, the learning activities require mostly *purist* and *doctrinal insight* (principles and procedures), with frequent shifts between these. Historic notes represent brief diversions to *knower insight*. In theory modules activities that require true *situational insight* from the student are difficult to realize, and therefore rare. Discussions of applications expose students to *situational insight* but does not require the student to engage in it. In the 3rd year laboratory module *purist*, *doctrinal* and *situational insights* are represented equally, with frequent *insight shifts* between these, especially between *situational* (possibilities) and *doctrinal* (accepted procedures) quadrants.

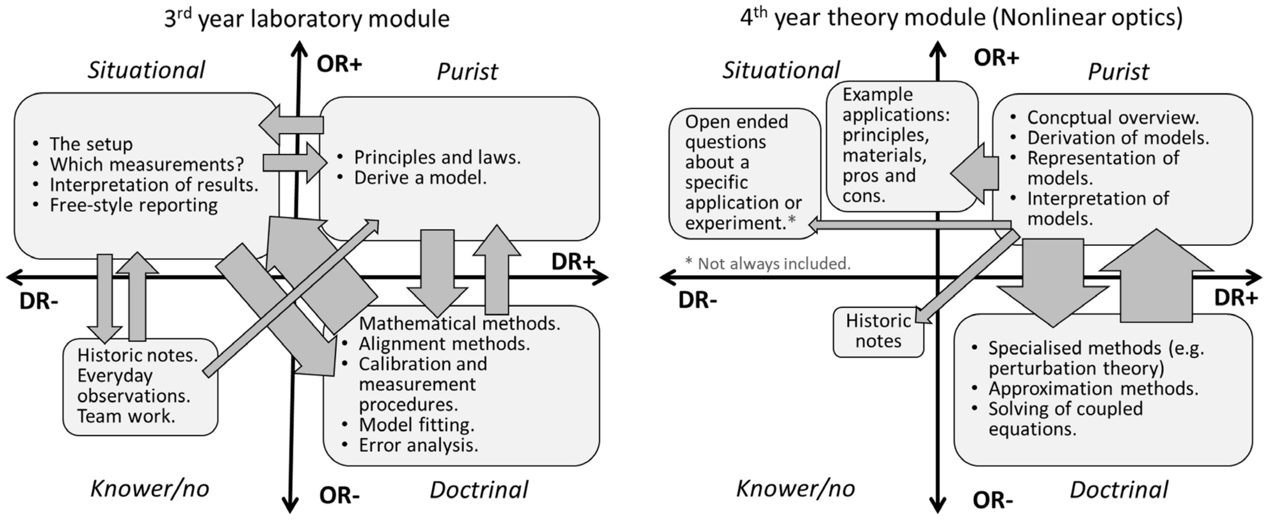

Figure 2. Analysis of *insights* and *insights shifts* on the *epistemic plane* in the 3rd year laboratory module (left hand side) and a representative 4th year optics theory model (right hand side). The sizes of the text boxes reflect the amount of time spent on activities requiring the relevant *insight* and the widths of the arrows show how frequently the relevant *insight shifts* are required.

In the laboratory module it is assumed that non-prescriptive guidance is given allowing the students to investigate the experimental setup, plan, execute and interpret the measurements with an appropriate degree of independence so that *situational insight* is required. Teamwork and application of everyday knowledge requires meaningful application of *knower/no insight*.

Informal discussions with postgraduate students who have completed these modules confirmed that the 3rd year laboratory module gave them the practice to make transitions between considering possibilities (*situational insight*), using legitimate procedures (*doctrinal*), and applying theory (*purist*). They mentioned that the lab work gave them confidence and made the theory of the 4th year less abstract. Some of the students highlighted the exciting ("wow!") experience of doing experiments on phenomena that were completely new to them.

4. DISCUSSION AND CONCLUSIONS

The laboratory module in the 3rd year introduces optics and photonics in a different way than theory modules would have done. The laboratory setting requires students to apply principles and procedures to situations where, from their perspective, different approaches are possible, and decisions must be taken in a team. This requires *insight shifts*.

We consider the findings from the studies in engineering education for perspective on the potential impact. The studies in mechatronics engineering education by Wolff et al. [5-7] are most relevant to our context. *Epistemic relations* were used to identify the engagement of different *insights* by early career mechatronics engineers during problem solving in their work environments. It was concluded that the most successful problem solvers were making multiple and conscious transitions between different *insights* while progressing through different stages of the problem-solving process[7]. They recognized which way of thinking was most useful at each stage, including applying disciplinary principles (*purist*) and legitimate procedures (*doctrinal*), but also considering different approaches (*situational insight*).

These conclusions highlight the importance of learning opportunities that require conscious shifting between different *insights*, as offered by our 3rd year laboratory module. Our labs-first program structure does not allow us to cover as many optics and photonics topics in the 3rd year as theory modules would have, meaning that 3rd year graduates are not fully specialized. In our context this is in order as students entering employment after the 3rd year usually go to diverse work environments where the ability to apply different *insights* will be more important than their physics specialization. For students continuing towards the 4th year and postgraduate studies the 3rd year laboratory module is essential training for their Honours research project. The students also value that the topics covered in the 3rd year laboratories give them concrete examples as reference points for the new abstract theory they encounter in Honours.

Offering the laboratory module before theory modules has the advantage that the assignments approach the authentic challenge of an unfamiliar problem and encourages students to engage in *situational insight*. It is important that the laboratory activities should be offered with appropriate non-prescriptive in-person guidance that allows students freedom to consider options and make decisions while providing support[11]. An added bonus is that 3rd year students appear to find experiments on new topics more interesting than experiments where they know beforehand what to expect, and this laboratory module has in the past attracted students to postgraduate studies in optics and photonics.

This paper demonstrates the use of the *epistemic relations* of LCT to analyze a program in optics and photonics. The analysis highlights the value of laboratory modules in preparation for problem solving. It shows that in specific contexts it can be motivated to offer a laboratory module as the first introduction into a field of specialization, before specialized theory modules are offered.

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