

How Do We Know? Inquiry-based Front Ends for Conventional Topic Treatments in STEM Textbooks

David Schuster

Mallinson Institute for Science Education, Western Michigan University

Abstract

Most conventional science textbooks present *what* we know, as an established body of knowledge, but little if anything of *how* we know. Science is presented largely as product, with the inquiry practices of science largely absent. To remedy this imbalance, we have been devising inquiry-based ‘front ends’ for use in instruction as precursors to direct textbook treatments. We illustrate the issue with an example of a direct textbook exposition of refraction, and then show this can be enhanced with an inquiry-based conceptual introduction to the topic. Similar inquiry-based front ends are being developed for other science topics.

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Introduction

“The fatal pedagogical error is to throw answers, like stones, at the heads of those who have not yet asked the questions.” (Tillich, 1979).

In conventional science textbooks and courses, students are presented with established scientific knowledge, but learn little if anything about how we got to know it in the first place. Yet at the very least, science is both process and product. It is not just a body of knowledge to be learned, although students might be forgiven for thinking so, judging by the way many mainstream textbooks portray it. Topics are typically presented as a ‘rhetoric of conclusions’ (Schwab, 1962), with the end-product facts, formulas and principles stated directly up front, for students to learn and then apply to end-of-chapter problems, which themselves tend to be fact- or formula-based.

Yet National Science Education Standards (National Research Council, 1996) advocate inquiry-based science education throughout K-12 schooling, while at college level the science curriculum reforms of the 1960s and beyond mostly took a scientific-inquiry approach to fundamental science. However, little of this is currently reflected in textbooks. There is little if any sense of discovery or the intellectual achievement involved, or of how one might go about it, even in principle. Yet ‘science’ is a multi-faceted endeavor, having at least three different ‘faces’ (Schuster, 2009): i. science as a *process* of discovery and knowledge-production, i.e. ‘science-in-the-making’, reflecting what scientists do and how they do it, ii. science as *product*, a body of knowledge, commonly presented to students as ‘ready-made-science’, and iii. science as *application*, in which scientific knowledge is used to solve problems, explain and predict, as well as being applied in engineering and technology. Science courses should ideally include all three faces in a balanced way, but this is rarely how topics are presented in textbooks. Yet knowledge is expanding all the time, and the ability to pose questions, investigate, produce new knowledge and tackle new problems is crucially important in all areas of STEM. This is recognized in the newly released Next Generation Science Standards

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(Achieve, 2013), which have an explicit major emphasis on the *practices* of science and engineering.

Example of a Textbook Topic Treatment

We illustrate a conventional expository treatment of a science topic by using the example of the refraction of light as presented in a high-adoption college physics textbook (Serway, 2000). This extract is chosen because it illustrates so clearly a concise direct exposition of content. The textbook account of refraction with accompanying diagram is given below.

Refraction

When a ray of light travelling through a transparent medium encounters a boundary leading into another transparent medium, as shown in the figure, part of the energy is reflected and part enters the second medium. The ray that enters the second medium is bent at the boundary and is said to be **refracted**. The incident ray, the reflected ray, and the refracted ray or live in the same plane. The **angle of refraction**, θ_2 in the figure, depends on the properties of the two media and on the angle of incidence through the relationship

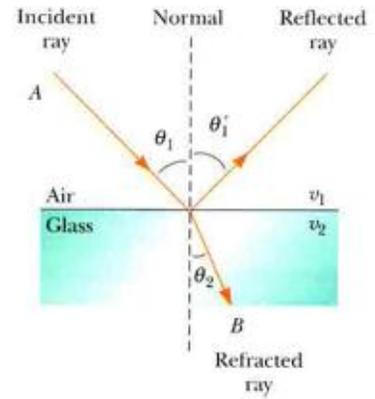
$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_2}{v_1} = \text{constant}$$

where v_1 is the speed of light in the first medium and v_2 is the speed of light in the second medium.

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In general, the speed of light in any material is less than its speed in vacuum. It is convenient to define the **index of refraction** in the medium to be the ratio

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$



This treatment is perhaps a rather extreme case of presenting science entirely as product; the expository narrative is a ‘rhetoric of conclusions’, focused on the refraction law formula. The phenomenon itself is minimally described, followed immediately by the law. Thus the same opening paragraph serves for both introduction and final-product knowledge. The physical phenomenon itself (a fascinating aspect of the behavior of light) gets short shrift. Note also that the account proceeds directly to a quantitative expression prior to any qualitative account of refraction behavior and its variation with angle. How refraction behavior was (or can be) investigated to arrive at this relationship between incident and refracted angles gets no mention. The book simply hands the law down as if ‘from on high’, in compact form. At the same time it also brings into it light speeds in the media, though this aspect has not yet entered the picture.

While ‘solid’ on the facts this treatment clearly does not reflect the nature of scientific inquiry nor the intellectual achievement of discovering the law, although the physics is correct, to be sure. This concise content presentation brings in refraction, reflection, light speeds and the refraction law all at once in a short paragraph; it is nothing if not efficient! However it seems more in the nature of a wrap-up summary of content than an approach to understanding to the topic for learners. The treatment, written by subject-matter experts,

reflects little heuristic, epistemological or pedagogical insight, instead focusing entirely on content. Presenting a topic this way arguably also misrepresents the nature of science, sending an unfortunate message to learners about what science is all about what learning science will be all about. It also tends to promote rote learning.

These shortcomings notwithstanding, a didactic exposition of this sort may appear at a cursory glance to be satisfactory, to many faculty or teachers prescribing textbooks, since it seems to be a correct and efficient account of the subject matter. Because it is a common and thus familiar approach, people may not recognize its deficiencies. Some may also view a textbook as a content resource rather than a learning resource and thus not easily see it from a learner's perspective. Some instructors may themselves teach science entirely as known product without any sense of how we know. Instructors who in fact recognize the 'experimental' aspect of science may still see that as a function of a separate lab course, to verify what was taught in lecture. Thus for various reasons, the science-in-the-making aspect, i.e. the intellectual achievement of doing science to produce knowledge, is notably absent, though it is arguably a central component of the scientific enterprise, and the expertise and abilities involved are important for both scientists and engineers.

Typical textbook problems

A textbook's implicit epistemic stance toward science and science learning is also evident in the types of problems set for students. Here is an example problem which follows the textbook presentation of refraction.

Example problem. An index of refraction measurement.

A beam of light of wavelength 550 nm travelling in air is incident on a slab of transparent material. The incident beam makes an angle of 40.0° with the normal, and the refracted beam makes an angle of 26.0° with the normal. Find the index of refraction of the material.

This formula-based algorithmic exercise is certainly well aligned with the book's approach to the subject! In the end-of-chapter problems too, there are few which emphasize physical insight and conceptual understanding, and we found no inductive or databased tasks or problems. The problems got harder to be sure, but their deductive formula-based character remained mostly the same.

Overall, we may characterize both the topic treatment and the problems as follows. The facts, concepts, principles and formulas are presented and explained directly to students, who are then asked to apply them deductively to solve quantitative formula-based end-of-chapter problems. The approach unfortunately tends to promote rote learning and algorithmic problem-solving. Such textbook treatments do not adequately reflect the full range of expertise in science, the nature of scientific inquiry, or the intellectual achievement of discovery and invention. There may be an unconscious assumption that some these other things may 'just happen' along the way or be taken care of in a lab course. One imagines that some may be tempted to say: "The content is solid, why worry about these other issues, the epistemology, pedagogy, or other facets of science? I just want my students to know the physics content and apply it to solve problems". Yet we ask: what tacit messages are being sent to students about physics and about learning physics? What is being valued and what not, and what is rewarded in grades? Which abilities are being promoted and which not? What will be the effects of this stance? We risk producing graduates who may 'know' a lot, much of which can be looked up, but who have little ability or experience in doing science for

themselves, or even how to go about in principle. It will be seen that this is partly a ‘curriculum’ issue, with important aspects of science being neglected. Since this is of great concern, we turn next to a possible way of addressing the problem.

Inquiry-based Front Ends for Conventional Textbook Treatments

Given the prevalence of the conventional content-centered direct expository approach in textbooks, what can one do about the situation when teaching? One way to go, other than writing a textbook oneself, is to devise inquiry-based front-ends for each textbook topic. That is, develop an introduction to the topic that provides the missing inquiry-process components, namely the phenomenon itself, the central questions arising, and how one might proceed to investigate and generate the new knowledge.

We exemplify this ‘enhancement’ approach, at college level, by describing an engaging inquiry-based lead-in to refraction, showing how to complement and ‘rescue’ the aforementioned epistemologically- and pedagogically-challenged textbook treatment. Our ‘invitation’ to refraction starts with the phenomenon itself, which can be by demonstration, illustration, or student exploration, engendering interest, and curiosity about whether one could find a general relationship between incident and refracted directions that would work at all angles. We next provide accurate diagrammatic ray data to students to work from, showing incident and refracted rays over a range of angles, as in figure 3.

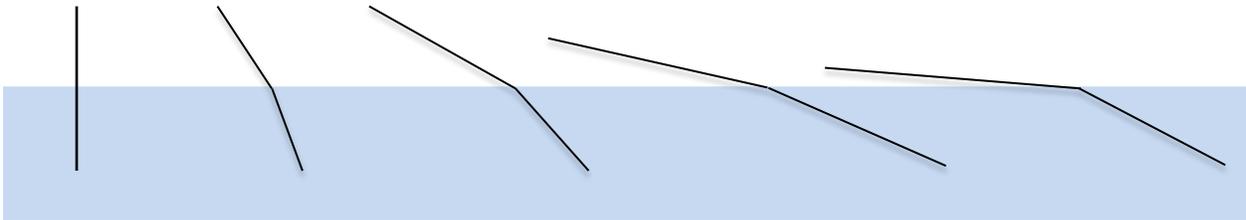


Figure 3. Refraction of light at various angles.

To go from the ray data to finding a general relationship is the challenge task! Looks easy? It challenged many scientists for many decades, about 300 years ago. However if the task is properly scaffolded, we find that it can be successfully tackled by students. Ideally, students themselves analyze the ray direction data, guided by the instructor in their search for a relationship. Note that this is easier to do using a geometric rather than trigonometrical representation, as was indeed the case historically (Schuster, 2011). After trying some promising possibilities that then fail at larger angles, students find one that works, and hence propose a law for refraction. For a lecture-only presentation, this inquiry process could be modeled by the instructor with whole class engagement. In either case the analysis leads to the formulation of what is today called Snell’s law, namely

$$\frac{\sin \theta_1}{\sin \theta_2} = \text{constant}$$

This approach to the law of refraction at the same time models important processes of scientific inquiry, i.e. the ‘discovery’ and intellectual achievement aspects of science, which are conspicuously missing from conventional courses. It’s not just about what we know but also about how we know. Another benefit is that the inquiry task of seeking a law also serves as an authentic inductive data-based *problem!* Here the challenging ‘authentic’ problem is to

analyze ray data to find a relationship. Inductive problems of this type can form something of a balance to the almost entirely deductive formula-based problems prevalent in textbooks.

Discussion and Conclusion

Note that this refraction example constitutes a considerably longer and more demanding front-end than most. Others can be quite short; in fact in simplest form they may involve only illustrating the phenomenon and considering the relevant questions before answering them. We are working on a front-end inquiry-based enhancement approach for a number of topics. Note that an inquiry introduction by no means necessitates a full-blown student lab activity. The enhancements are to be seen as inquiry-narrative approaches to a topic, and can certainly be used with lectures, where the rhetoric changes from one of conclusions to one of inquiring, discovery and concept invention, leading to those conclusions. Questions certainly come before answers. Front ends do take some time at the start of a topic but can usually be quite efficiently done. It is well worth it, both for the portrayal of science and for better understanding the topic by contextualizing and making sense of it. Even a ‘theoretical’ lecture can provide a sense of how we know, not just what we know. The enhancements provide important aspects of science and pedagogy often absent in conventional treatments, and have the advantage of thus allowing one to use a wide range of existing textbooks.

Refraction has become one of our best exemplars of inquiry-based science teaching and learning for a topic. Students sometimes spontaneously remark that the challenge is unusually ‘real’ and engaging. Of course it also reflects the historical challenge of discovering the law. More broadly, creating inquiry-based front ends for textbook topic treatments can be a practical and effective way of improving science courses and enhancing their character, without having to write completely new materials. This could have broad impact if such inquiry-based introductions were created and made widely available for a range of science topics. At present we are devising inquiry front ends for chemical equilibrium, Newton’s laws of motion, mitosis, photosynthesis, Archimedes principle, and the seasons.

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Author's Information

David Schuster holds a joint appointment in the Physics Department and the Mallinson Institute for Science Education at Western Michigan University. He was previously at the University of Natal in South Africa, where he also served as national moderator for all matriculation physics examinations, and thereafter Chief Examiner for Physics for the International Baccalaureate. His research and development interests in science education include cognition, assessment, instructional design, inquiry, conceptual understanding and problem solving.