

The Development of Formative Assessment Probes for Optics Education

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ABSTRACT

Research exploring students' knowledge of optics from elementary through college has revealed that many concepts can be difficult for students to grasp. This can be the case particularly with fundamental concepts, such as the nature of light, how light interacts with matter, and how light behaves in optical systems. The use of formative assessment probes (low-stakes questions posed to students before instruction or in real-time in the classroom) can inform instructors about student background knowledge, and can also be used as they progress through learning in class. By understanding what students know prior to instruction, and how well they are learning in real-time, instruction can be designed and modified in order to encourage the development of scientifically-accurate knowledge.

Keywords: optics education, pedagogy, optical concepts, assessment

1. INTRODUCTION

Teaching a concept in optics requires a mastery of the concept by the teacher and an understanding of the relevant pedagogical approaches that are possible. It also requires sensitivity to possible non-scientific conceptions or naïve theories held by the student. To properly approach a teaching situation the instructor must have a clear notion of the student's conceptual knowledge level in order to properly select an appropriate pedagogical approach and apply the appropriate pedagogical content knowledge.

Much of the optics assessment research in education to date has focused on determining content knowledge of particular groups (e.g., middle or high school students, college students, teachers), typically as part of broader tests of physics knowledge. These diagnostic assessments have been discussed elsewhere¹. While these kinds of understandings are valuable, this paper describes how the content knowledge of each individual student can be assessed by an educator.

2. THE PURPOSE OF FORMATIVE ASSESSMENT

Imagine you are at a reunion. All of the people you most wanted to see are there and you pull out your trusted digital camera to record the occasion for posterity. The group joins together and says "cheese" as you collect the image. Almost immediately, the CCD outputs the recorded image to the camera's memory as well as to the screen on the back of the camera for your review. You notice that the figures are slightly blurry, that several people have their eyes closed, were clearly not paying attention as you were taking the picture, or had otherwise unsmiling expressions on their faces. You provide the group with some feedback, "That one came out blurry. Also, Joe and Jane, your eyes were closed, Sue, you weren't looking at the camera, and Peter, you weren't smiling. Let's try this again." You decide to sit on a chair nearby to steady yourself and the camera to reduce the blur, and hopefully, with the feedback they received, Joe, Jane, Sue, and Peter will improve their appearance in the photo. You re-record the image. Once again, you review the image on the display screen on the back of the camera. This time it's clear, and the picture is one of all smiles.

Now imagine that you don't review the image when it is taken. Instead, you snap the picture, the image is recorded to the camera's memory, and you assume that because you are a fairly accomplished amateur photographer and you clearly said "1-2-3-cheese" to indicate when the picture would be taken, it will appear as you imagined. You return home after a lovely reunion and load the image onto your computer. You are disappointed to see that the image is blurry, and that several of the individuals are looking in other directions, talking, or blinking. Also, the entire picture is underexposed.

Had you reviewed the image right after it was taken it would have been easy to adjust the conditions of the picture and re-take it, but now it's too late; there's no going back and re-capturing the moment. In an analogous way, formative assessment in education gives the teacher an opportunity to take a snapshot that can be enormously useful in understanding the cognitive state of the student.

3. PRIOR KNOWLEDGE AND LEARNING

With the emergence of cognitive science research, which describes learning as the active construction of knowledge structures by the mind of the learnerⁱⁱ, we know that learners do not necessarily “learn” exactly what they are “taught.” The mind is not a camera that objectively and precisely captures reality, rather it is a system of successive filters based on prior knowledge, experience, learning environment, mood, etc. As in the photograph example above, the “pictures” (an analogy for what is learned) in the minds of some learners will turn out clear (that is, close to accepted scientific knowledge); however, some will also turn out blurry, out of focus, or off-kilter. What and how well people learn is highly dependent upon a constellation of internal and external factors, including their own level of prior knowledge of the subject, how and in what context they are taught, their learning styles, what materials are used to teach, the behavior of their peers, etc.

One of the most important of these factors is undoubtedly a student's prior knowledge of the subject. What students already know about a subject, their prior knowledge, is a critical factor in what they will learn about that subject. Prior knowledge acts as a framework that new knowledge is connected to or hung on, and often, that prior knowledge is “scientifically limited or incorrect”ⁱⁱⁱ. In the field of optics, we often assume that students know fundamental ideas about how light behaves, but research on student conceptions has shown that this is not necessarily the case. A few core ideas in optics are listed below³. While these ideas may be rudimentary for experts in optical science, we cannot assume that the audiences we are working with necessarily understand them.

All objects (experienced in our everyday lives) reflect and absorb light, and some objects also transmit light.

Dark or black objects mainly absorb light; light or white objects mainly reflect light.

There is an inverse relationship between light reflected from and absorbed by an object: more reflected light means less absorbed light.

Light reflects from objects in a particular way: the angle of incoming light equals the angle of reflected light.

What we see is light reflected from objects.

There must be a source of light for us to see an object.

Sources of illumination can produce light (e.g., the sun) or reflect light (e.g., the moon).

When an object blocks a source of light, a shadow is formed. Shadows are dark because there is no light reaching them to be reflected to our eyes. The distance of an object from a source of light it blocks determines the size of the object's shadow. The shape of an object's shadow depends on the angle of the object to the light, so the shadow of an object may have more than one shape.

The color of an object is the color of light reflected from the object.

The colors of light come from white light, which can be separated into many colors.

The color of an object depends on the extent to which particular colors of light in white light are reflected and absorbed.

Prior knowledge is based on personal experience collected, organized, and built into an explanation of how the world works in the mind of the individual. For example, “[T]here is a widespread belief [conception] that the earth's seasons

are caused by the distance of the earth from the sun rather than by the angle of the earth's axis with respect to the sun . . . Many experiences support the idea that distance from a heat source affects temperature. The closer we stand to radiators, stoves, fireplaces, and other heat sources, the greater is the heat³. But often, every day experiences are insufficient to construct scientifically accurate models for underlying phenomena, such as with the cause of the seasons.^{iv} What the educator needs to do is know what knowledge students are bringing into the classroom, engage those pre-conceptions, and tailor teaching to address and help students correct these by providing accurate information and effective experiences to help students learn. This is far easier said than done, since each individual literally has a different "picture", that is set of knowledge in their head about any given phenomenon, and some of these ideas are more resistant to change than others. Over the past decades of studying what students know about science, we now understand that "[s]imply telling students what scientists have discovered . . . is not sufficient to support change in their existing preconceptions about important scientific phenomena"³. Some prior conceptions can require extensive new experiences of the "right" kind with opportunities for students to carefully think about how their prior conceptions are not accurate and why the new conception is accurate. This process of changing a deeply held conception, "conceptual change,"^v forms the rationale for the "inquiry" or "experiential" learning movement that is the currently accepted framework for teaching science at the K-12 levels in the US.

4. ASSESSING LEARNING

In order to know what students know or whether they are constructing scientific knowledge accurately, the use of various assessment strategies is key. Assessment is the process of making what students know transparent by asking them questions in writing (e.g., on an exam or problem set), asking aloud (e.g., during class or in individual meetings or office hours), or asking them to perform some skill (e.g., setting up and conducting an experiment). The more in-depth their understanding, the more students are able to "do" with the information or make inferences from what they know.

However, each learner is unique. The structures of knowledge that have been built by novices are very different from experts, not only in level of depth, but also in organization and ease of recall. Their depth of knowledge allows experts to perceive patterns in information that may be invisible or unrecognizable to novices. The first step in assessing learning is starting out at a general level appropriate for the average learner in the class. This is often accomplished through a diagnostic knowledge test (e.g., quiz on the first day of class or at the start of a new unit) to provide a baseline of student prior knowledge relative to the subject or topic.

One framework for classifying depth of learning is Bloom's Taxonomy of Educational Objectives^{vi}. Bloom's taxonomy describes what an individual can do with knowledge depending on how deep their knowledge structures may be. The six levels range from the most rudimentary, "Knowledge", in which an individual can only recall or recognize facts, to "Synthesis", in which an individual has all of the preceding levels of knowledge and can actually create new knowledge, products, or projects. Table 1 lists the most recent version of this taxonomy^{vii}. The most novice learners (Level 1 in Table 1 below) will be able to recognize and recall basic facts about light (e.g., Light travels in a straight line.). While the most expert (Level 6), will be able to create new products, knowledge, related to a particular content area (e.g., design a device that tests whether light is traveling in a straight line). Once the general level of learner is known, the teacher can determine the depth of student learning relative to the end goal or objective.

Bloom's taxonomy is a useful heuristic to determine what level of knowledge students have achieved and should achieve. Often students have achieved different levels of knowledge of different concepts. It is quite common for students to be able to work at higher levels of knowledge for very concrete, everyday phenomena, and at lower levels for more abstract, rarely explored phenomena. For example, in the case of index of refraction many introductory undergraduate students can often explain (Level 2) and apply (Level 3) Snell's law in a problem set to calculate indexes of refraction when given the right combinations of variables, but would likely have difficulty if asked to design an experimental procedure (Level 6) to measure the index of refraction of a material with error of 1% or less. The larger the disparity between the student's current level of knowledge and that which needs to be reached, the more learning which will need to take place, and therefore, the greater the learning curve.

Table 1: Levels of depth of knowledge.

Level	Depth of Knowledge	Student Outcomes A student with this level of knowledge will be able to:
1	Knowledge	Retrieve relevant knowledge from long-term memory. Includes recognizing and recalling.
2	Comprehension	Determine the meaning of oral, written, and graphical information. Includes interpreting, classifying, summarizing, comparing, and explaining.
3	Application	Carry out or use a procedure in a given situation. Includes executing and implementing.
4	Analysis	Break material into its constituent parts and detect how the parts relate to one another and to an overall structure or purpose. Includes organizing, attributing, and differentiating.
5	Evaluation	Make judgments based on criteria and standards. Includes checking and critiquing.
6	Synthesis	Put elements together to form a novel, coherent whole or make an original product, project, knowledge, etc. Includes generating, planning, and producing.

In addition to the level of knowledge expected of students, it is also key to consider the various types of knowledge involved with the topic. There are four main knowledge domains: factual, conceptual, procedural, and metacognitive. Table 2 lists and describes each of these types of knowledge. Each level of Bloom’s Taxonomy applies to each knowledge domain, and students need to have knowledge in each domain to succeed in learning. For example, in the case of index of refraction, factual knowledge includes terminology (e.g., speed of light, refraction, index of refraction) and specific details (e.g., the value of c), conceptual knowledge includes interrelationships (e.g., index of refraction, Snell’s law), procedural knowledge includes the ability to select when Snell’s law is an appropriate solution to a problem or situation as opposed to other physical principles, metacognitive knowledge includes the ability to respond appropriately to a problem on index of refraction for the context of a physics course (e.g., knowing it is appropriate on a physics exam to calculate a mathematical solution rather than writing a poem about refraction, knowing to draw a picture to visualize the solution to a problem for a learner who finds this a helpful strategy).

Table 2: Types of knowledge.

Factual The basic elements that students must know to be acquainted with a discipline or solve problems in it. (e.g., knowledge of terminology, specific details and elements)	Conceptual The interrelationships among the basic elements within a larger structure that enable them to function together. (e.g., Classifications and categories, principles, theories, models)
Procedural How to do something: methods of inquiry, criteria for using skills, algorithms, techniques, and methods. (e.g., Subject-specific skills, criteria for determining when to use appropriate procedures)	Metacognitive Knowledge of cognition in general as well as awareness and knowledge of one’s own cognition. (e.g., strategic knowledge, appropriate contextual and conditional knowledge, self-knowledge)

Using the 1) level of the learner’s current knowledge, 2) level of knowledge that needs to be reached, and 3) type of knowledge, we have a heuristic for determining what and how well students should be learning. Having discussed structures of knowledge, we will now discuss how assessments can be used to make student knowledge transparent.

5. FORMATIVE ASSESSMENT

As in the photography example at the start of this paper, formative assessment measuring quality of experience in real-time is used continually to improve and enrich our daily life experience. Yet in the classroom, in this age of summative, high-stakes, standardized testing, it does not receive the same attention in discussions of teaching practice, despite the research results that have shown it is crucial for effective learning to take place^{viii,ix}. Unlike other forms of assessment, such as *diagnostic*, which is used “[t]o identify preconceptions, lines of reasoning, and learning difficulties,”^x prior to instruction, or *summative* assessment, used “[t]o measure and document the extent to which students have achieved a

learning target”¹⁰, after instruction to evaluate student learning outcomes or teaching effectiveness; *formative assessment* is conducted in real-time as learning is taking place.

While diagnostic and summative forms of assessment are designed to inform teachers, administrators, or others about what students know, students may or may not glean direct instructional benefits from these. This is especially the case with summative assessment, which often takes the form of high-stakes, end-of-unit or-course tests, and are used only to evaluate student learning. In contrast, formative assessment has a very different function. Its purpose is much like reviewing the picture on the digital camera to determine whether it is “acceptable” or whether something needs to be done to improve the conditions and retake. Formative assessment serves these multiple purposes.

Formative assessments – ongoing assessments designed to make students’ thinking visible to both teachers and students-are essential....They permit the teacher to grasp students’ preconceptions, which is critical to working with and building on those notions. Once the knowledge to be learned is well defined, assessment is required to monitor student progress... to understand where students are in the developmental path from informal to formal thinking, and to design instruction that is responsive to student progress. An important feature of the assessment-centered classroom is assessment that supports learning by providing students with opportunities to revise and improve their thinking¹¹.

Therefore, formative assessment not only provides the teacher with information about what and how well students are learning in order to re-teach or changes teaching strategies as needed, but also provides students feedback about what they are learning so they can modify their learning strategies. Feedback to students is critical here, and the ability of the student to critically examine one’s own knowledge by completing the assessment, receive feedback about the current state of that knowledge following the assessment, and determine what needs to be done to improve that knowledge is the mechanism by which learning takes place.

The way formative assessment fits in with instruction is through the model of a continuous cycle of assessment and teaching, with feedback to students at critical junctures that enable them to reflect on their own learning and to both improve on their own as well as indicate to the teacher what needs to be changed in instruction to re-teach or teach differently in real-time. The key questions to be asked when designing instruction and teaching are given as:^{xi}

1. Where are you trying to go? (identify and communicate the learning and performance goals);
2. Where are you now? (assess, or help the student to self-assess, current levels of understanding);
3. How can you get there? (help the student with strategies and skills to reach the goal).

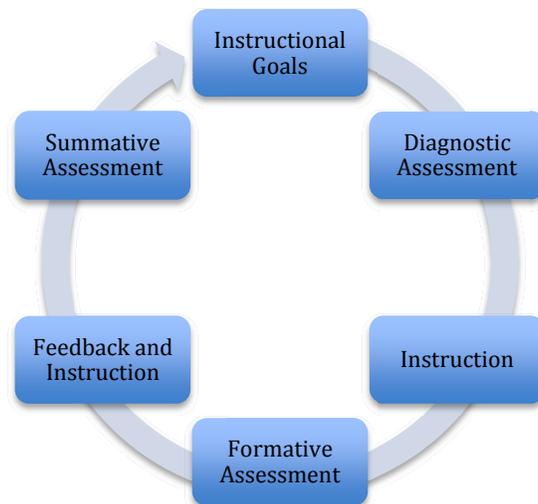


Figure 1: Integrated Instructional Design Model.

The integrated instructional design model is shown in Figure 1. This instructional design model applies to any level of education (K-adult) and teaching in any setting (formal, informal), as it is based on fundamental principles of how all humans learn. In the next section, examples of formative assessment probes in optics are presented.

6. FORMATIVE ASSESSMENT PROBES

Many instructors ask students review questions informally throughout their lessons to determine how well students are learning. While this is a form of formative assessment, what we are advocating is for a more systematic way of assessing learning that is specifically aligned with what students are expected to learn from the lesson, course, or program.

Typically ungraded and asked during class right after teaching a concept, formative assessment probes are specific questions that help both the educator and the student determine the students' levels of knowledge. They may be merely a question posed to students after teaching that they need to answer in writing, orally, or by completing a skill task, or they may be combined with the use of discussion or the use of clickers. The most important idea here is that formative assessment probes are closely linked to what students should be learning and they occur as soon after teaching as possible. Many instructors use questions at various points during lecture (e.g., lecture for 10-20 minutes, ask a question). These questions may be very straightforward (e.g., What is refraction?) or more complex (e.g., Based on what we just learned about lenses and image formation, draw a sample partial lens with ray diagram and explain how partial lenses form images). They may include illustrations, be combined with demonstrations in class, or specific laboratory tasks. This is why formative assessments “work” for learners of all ages (e.g., elementary, middle, high school, or college students); they are tailored or selected for a particular program of study, course, or lesson with those learners in mind.

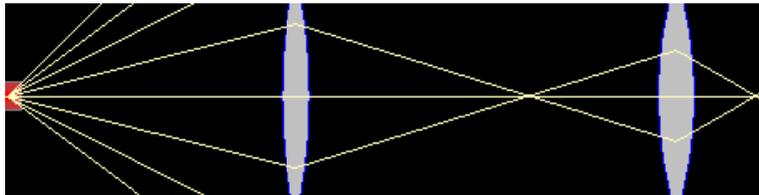
The first step in selecting or creating a formative assessment probe is determining at what level of knowledge students are – more novice or more expert (e.g., using the levels of Bloom's taxonomy); second, determining the objective level which you want them to reach (also using Bloom's Taxonomy); finally, what knowledge dimension is expected; these combined factors will determine what type of assessment is most appropriate. Examples of three formative assessment probes are provided below with descriptors for the level of knowledge desired and knowledge type. These questions would be appropriate to ask students during class immediately after a lecture, lab, or demonstration, on index of refraction before moving on to the next material.

Example 1: Simple Refraction (Objective Level = 2, Knowledge Types = Conceptual, Metacognitive)

When you look down into an aquarium, the fish you see appears:

- a. deceptively large
- b. deceptively small
- c. the size it would appear if there were no water^{xii}

Example 2: Speed of Light, More Complex Refraction (Objective Level = 2, Knowledge Types = Factual, Conceptual, Procedural, Metacognitive)



A

B

C

Figure 2: Telescope Optics (http://webphysics.davidson.edu/physlet_resources/optics4/default.html)

If light rays start out from a light source together at the same time at location A and pass through an objective and an eyepiece of a telescope to arrive at location C, which ray(s) arrives first and why?

Example 3: Index of Refraction (Objective Level = 3, Knowledge Types = Factual, Conceptual, Procedural, Metacognitive)

A light wave in air is incident on a boundary with ethyl alcohol (index of refraction 1.36) at a 30.0° angle. At what angle does the refracted ray leave the boundary?^{xiii}

Many formative assessment probes are questions similar to those asked on diagnostic, midterm or final exams, or questions from the end of textbook chapters. Using questions like these, not only provide insights into student learning, but also give students practice with the types they will see on the exams.

7. CONCLUSION

A good formative assessment probe not only tells the teacher what a learner knows about a subject, and how deeply they are able to work with that knowledge, but they are also aligned with what learners need to know and be able to do by the end of the lesson, course, or program. The best formative assessment probes combine tests of learning with learning by doing (e.g., having students think, write, and discuss their answers; having students observe a demonstration and predict the outcome based on previous lessons). The best probes are also tailored to the audience. For younger or more novice learners, it is best to keep assessments limited to one major concept and rooted in concrete, physical phenomena familiar to learners; whereas, more experienced or expert learners can be assessed on multiple concepts at deeper levels of knowledge (e.g., analysis, evaluation, and synthesis in addition to knowledge, comprehension, and application) and testing multiple forms of knowledge (factual, conceptual, procedural, metacognitive) to reveal the breadth and depth of their learning in order to solidify or clarify their existing knowledge structures and prepare them for effective future learning.

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