Theory and practice: how do we teach our students about light?

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ABSTRACT

As optical scientists and engineers we have an educational paradigm that stresses passing knowledge from
teacher to student. We are also taught to use inductive reasoning to solve problems. Yet many of the
fundamental questions in optics such as the topic of this conference “What are photons?” require that we use
retroductive reasoning to deduce the possible and probable cause of the observations and measurements we
make. We can agree that we don’t have all the answers for many fundamental questions in optics. The
retroductive reasoning process requires a different way of thinking from our traditional classroom setting. Most
of us learned to do this through working in a research lab or industry. With the amount of information and new
discoveries to consider, it makes it difficult to cover everything in the classroom. This paper looks at
transformational learning techniques and how they have been applied in science and engineering. These
techniques show promise to prepare our students to learn how to learn and develop skills they can directly apply
to research and industry.

Keywords: Optics education, transformational learning, scientific inference, science education.

1. INTRODUCTION

A few years ago I began working with an interdisciplinary group of scientists. I kept being asked very basic questions
about light and optics that I realized I didn’t know the answers to. What I had learned in the classroom through a BS,
MS and PhD in optics had not prepared me to answer these questions. Neither had my 20+ years experience in industry,
academia and consulting. Most of these questions were fundamental science questions. Things like why don’t light
beams bounce off one another may seem like a simple and obvious thing to an optical scientist or engineer. But have
you ever tried explaining that to a biologist, MD or a psychologist? So many of the questions I got were of the “what is”
type. In the classroom my professors had been like Adolph Lohmann who once said “Let us be modest “what is” cannot
be answered in science.”[1] He was content to “leave the “what is” question to be dealt with by philosophers and
theologians.”

Our education system (at least the schools I went to and have taught at) stress the approach of passing knowledge from
one generation to another. Most of the time the “guru” taught everything he or she knew with endless equations and
facts on the blackboard and lots of homework problems to solve. There was not much space for fundamental questions,
interactive discussion or reflective thinking – all necessary skills for performing scientific research. I learned what I
needed to for each class and didn’t do much questioning in terms of how it fit together unless I was trying to do
something in the laboratory. Most classes had a textbook that was only basically followed. We usually used the sign
convention the professor preferred and that often wasn’t what was in the text or the same as another class. There were
times when my classmates and myself were thoroughly confused.

What I noticed was that optics was contextually based. The particular facts as understood for a particular course
depended upon what types of problems we were trying to solve. We learned to do first order optics to find an image
plane, trace rays to determine aberrations, do Fourier transforms to figure out diffraction patterns, use electromagnetics

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for wave theory and quantum mechanics to think about individual photons. Yet in all this there never was one theory that could be used for everything. It simply was not practical to use quantum mechanics to find an image plane.

So in all that, I never thought much about some of the really basic things when I was in school like how come light rays don’t bounce off of one another. What really is happening when light reflects or scatters off a surface? Is there light in the dark? Or, how the heck is it we can see anything at all if there are photons carrying all sorts of information in every possible direction that go on for ever and ever?

The fundamental questions of light have had me thinking about them for most of my life. I am intrigued by the varied answers offered by a large array of scientists. I truly enjoyed seeing the special issue of Optics and Photonics News titled “What is a photon?” edited by my co-chair Chandra Roychoudhuri.[2] At last a colleague was asking similar questions. These questions were truly the birth of this conference series on the nature of light.[3-5] I brought the idea to Chandra of getting as many scientists together as we could to look at these questions. Our first conference was a success and stimulated discussion than went on for half a day after the conference ended. These are the kinds of conferences I truly love organizing and attending.

More than thirty scientists gave their views on “What is a photon?”[4] When it was done the agreement was basically that a photon is a mass-less blob of energy that contains the information of what it has interacted with. Last year we looked at some of the questions about “Light in Nature”[3] and this year we’re back to “What are photons?”[5]

Ultimately I do believe that asking some of the “what is” questions are not only important for us, I think it is necessary to bring these subjects up in the classroom and have students think through some of them. Some of the properties of light are truly profound. Those of us with a touch of awe are the ones asking the tough kinds of questions we are asking in this conference.

2. INNOVATION AND DISCOVERY: THE SCIENTIFIC PROCESS

Scientific paradigms come and go, albeit many take a long time to change. Recall how long it took before Galileo was vindicated. Many of us may never see the fruit of our labors in everyday technology but we do enjoy making new discoveries and heading down the less trodden path.

When we learn about the scientific process usually we are thinking about hypothesis driven research. Hypothesis driven research uses inductive reasoning. To put it simply, we form a hypothesis about some concept or physical process we are observing and then set about to prove it. This is basically, if ... then ... This works when we can isolate a single mechanism and test it.

However, the predominance of fundamental science experiments requires retroductive reasoning.[6] We observe a phenomenon and then we set about determining what caused that to happen. A great example of this is the big bang in astronomy. It is one theory that explains much of the data observed by astronomers. It is not the only answer that can explain the observed data. And as more and more new data are discovered that challenge a particular explanation, retroductive inference is further applied to hone the theory and account for new data.

You can think of retroductive reasoning as similar to optimizing a lens in a lens design program. There are many variables and the program is looking for a solution that will create the desired outcome (merit function). When solving an optimization problem it is desirable to find the global minimum in solution space. This is believed to be the “best” solution. Because these problems have so many variables, there is not one answer. Hence we have many different theories for different contexts. An excellent treatise on different types of scientific reasoning is given in Ernan McMullin’a monograph “The Inference That Makes Science.”[6]

The reason I’m bringing this up is because our teaching methods are predicated on how we reason scientific problems. We like to think that everything is inductive if... then..., but most of the phenomena that optical scientists deal with theoretically and experimentally is retroductive. Essentially, in most classes, especially with undergraduates, we are teaching our students how to apply inductive reasoning to solve scientific and engineering problems. Yet, when faced with real-world observations and experiments, and colleagues asking us tough questions, we need to be able to switch to retroductive reasoning.

In my real-world experience I predominantly encounter problems that require retroductive reasoning and “thinking differently” (to borrow from Apple Inc’s Think Different ads) in order to find a workable solution that solves the
problem and satisfies the customer. When I put on my optical engineering hat and help a consulting client with a measurement problem, most of what I use is retroductive reasoning.

As an example, I may look at some measurement inconsistency in an interferometer and then deduce what may be the cause of that. I then consider each possible mechanism individually and apply inductive reasoning to each. This could also be a hit or miss approach, but adding in many years of experience makes it possible to narrow down the possibilities quite quickly. When skilled engineers and scientists apply all their years of experience to this type of problem they are more like craftsmen and artists. These are often the hardest concepts to teach.

How do you teach these sorts of skills that students need in the real world? How do you get across the point that there is not just one answer to most questions? In the next section we’ll look at some different teaching methodologies.

3. TEACHING METHODOLOGIES

Optics is one of the most complex subjects to teach. We have so many different models that work in different situations. Are we talking about paraxial optics, geometrical optics, wave optics, classical or quantum electrodynamics, quantum optics, atom optics, etc.? And even though we have all these models, how do we get across simple concepts of light?

Do we really know what light is? I can ask a series of simple questions that most PhD’s cannot answer relative to light. We simply don’t have the definitive answers. We are dealing with data from personal experience, observations and empirical experiments. But the very nature of light still iludes us as we can see from the papers in this conference and its predecessors. We work backwards using inductive reasoning to try and explain different phenomena. However, many of them we know no more about than we do about the origin of the universe. So we hypothesize there was a “big bang.” That could explain the cosmological phenomena we observe, but everyday scientists report new findings that contradict that hypothesis. So what do we believe? How do we teach our students?

3.1 My Experience as a student

When I went to school it was mostly the teacher going through fact after fact and derivation after derivation and us students expected to soak this up and then regurgitate it in an exam. It was surface learning. You learned what you needed to pass the test and that was that. It wasn’t deep learning. It didn’t require learning to think or learning to apply the scientific process until I got to graduate school.

My first big aha came the summer after my junior year when I worked at Bell Labs as a summer intern. It was the first time I’d seen real optical components on a table doing something I’d only seen before as diagrams on a chalkboard or text book descriptions. The lab classes I’d had before this isolated small pieces of things with 40-50 year old equipment that was not in good shape. I’d never seen a high quality front surface mirror before. I’d never worked with electrical engineers, programmers, and technicians as a team to build a proof of concept, let alone been in charge of my own project. It was eye-opening.

My next aha came when I began working in a research laboratory. I was told to align a laser. Well, none of my labs had taught me the skills needed. I had a written procedure to follow. There was something about putting a mirror at Brewster’s angle. I asked an older student how I could tell that. I got quizzed about what Brewster’s angle was. He said use a polarizer and left the room. I started playing with the polarizer and tilting the mirror and voila, one polarization extinguished, and I was hooked on this optics stuff. That theory really did explain something. I didn’t need all the theory to line up the laser or determine Brewster’s angle, but I could use that knowledge to accomplish a goal. This was definitely a turning point for me. This was truly transformational.

After I realized that I learned most from what I did in the lab, equations on paper just weren’t the same. I still had most classes in graduate school as rote learning. I’d even say the same thing about my preliminary exams. They were about learning how to pass the test, not necessarily about synthesizing the material or what it meant.

One notable exception was a self-paced graduate lab class that took me thirty hours a week. The first week we had to build a working power supply. The next week we built a densitometer using the power supply. The next week we added microprocessor control to the densitometer using a Z80. In another module I had to make a 2-element eyepiece from 2 glass blanks in 2 weeks having previously never set foot in an optics shop. The next 2 weeks I had to test it
interferometrically and verify its paraxial properties. This was the most intense course I ever took and I learned more from it than any other.

It really wasn’t until I went back to school for my second PhD (which is in music) that I really thought much about teaching techniques. I had taught optics classes for 10 years before that, never really thinking about teaching methodologies. In lab courses I would have students do a series of experiments over the course of the semester that would lead them through a bunch of difficult concepts. They learned through coaching from myself and the TA, as well as some tasks that required reflection and writing down what they had learned.

In the lecture courses I taught using basically the same model I had been taught by, except that assignments and exams were more open-ended to make them more like problems they’d get in the real world. I gave take home exams where students could look up anything they wanted. I’d give spec sheets and ask them to write procedures or do basic design setups to solve a real world type problem. I only ever had one student call a manufacturer to ask about a spec. That’s out of over 100 students who took that course over 3 years. And she was an engineer who was taking the class as a distance learner. With other problems that could’ve been easily looked up in any technical library at a university or a large company, maybe 5-10% of the students would look it up. Even though the answer was there to be found, most never ventured to look for it. Instead they guessed.

When I went back to school after 10 years of optics teaching it was to fulfill a lifelong dream to study music. I also wanted to learn to think differently. A final exam of “name that tune” from Mahler Symphonies is about as far as you can get from a quantum optics exam. I observed how each professor taught. Most professors, especially in music history, used the same informational-based learning that I had gotten in optics. But some did things very differently. Some of my favorite classes were seminars where we each did research on a specific part of the topic and made presentations to the class. The questions and discussions were so illuminating. Your performance and grade was based upon achievement and learning and not based on competition. In these classes I learned so much more and it was fun. I could choose what I wanted to learn!

My biggest aha in teaching came from a psychology of music class I took one summer. The professor’s research area was music education. This was the first educational theorist I’d ever had a class from even though by this time I’d had 4 or 5 classes in music pedagogy. This was a 5-week long class that met 2 hours a day. Each week was a different unit with a test at the end of the week. For each unit the professor used a different style of teaching. As we went along I didn’t think I was learning much, but at the end of it I was amazed how much I had learned, especially when I wrote my research paper. It had been fun. It was totally interactive and engaging. Yes, there was reading and homework and research, but the class was guided by what we wanted to learn as well as following guidelines of what basic knowledge and concepts we needed to get from the class. I realized there was a totally different way to teach.

In the years since that class I’ve attended many workshops and short courses in all types of subjects. In one of them the topic came up about the difference between “informational learning” and “transformational learning.” That’s when I found that the teaching techniques I had adopted from my psychology of music class were transformational. Transformational learning techniques are about changing how a student thinks.

### 3.2 Transformational versus Information Learning

Informational learning is the paradigm most of us are used to. It is the model where the professor goes through the material in lectures, students do homework problems and read the text to reinforce these concepts. The test material is generally taken directly from the lectures, homework, and text. Students in these types of classes learn techniques to pass the class, get their B, or ace it with an A. From my experience it’s obvious from the beginning of the semester which category a student falls in. I know from my own experience that I can cram for a test, ace it, and then forget most of it within a week. There’s simply no use for that “excess” information. It hasn’t become a part of me. For many students it’s all about passing the test and getting a good grade. There are studies that show that within a few weeks on the order of 90% of the information a student learns in a class is forgotten. (see for instance [7, 8]) I know from my own experience this is true.

At first I thought the key was to find ways that students could retain more and use those kinds of teaching methods. Remember things you had to memorize in grade school? Did you really learn that? How much do you still remember?
Instead I realized the key was to teach students how to do research, how to learn on their own, how to find what they needed and be able to recognize what was high quality information. Then there is that 10% they’ll remember. What are the really key concepts and bits of information that they need to know and retain? I began to experiment with different ways of teaching and having them teach each other while concentrating on that 10% and having them learn how to learn and think differently. I later realized that these are some of the basic tenets of transformation learning.

The concept of transformational learning began in the context of adult education with non-traditional students in the late 1970’s [9]. Educators recognized that the real life experience these older students had gave them tools that shaped the way they looked at things as well as providing a different way to learn. In many cases classes they took transformed their whole way of thinking or being in the world.

We know that people learn differently. Some memorize. Some are good listeners and remember everything from a lecture. Some retain all they read. Others do best solving problems. Others need to work in small groups. By the time a student gets to be a senior in an undergraduate program they generally know what works best for them. Setting up a class that accommodates as many different types of learning as possible helps the students get the more difficult concepts.

A commonly accepted definition of transformational learning as described by M. Carolyn Clark is “learning that produces change” and a common characteristic is that “transformational learning shapes people; they are different afterward, in ways both they and others can recognize.”[10] Clark continues on to point out that “transformational learning is, in short, a normal part of our lives and intimately connected to the developmental process.” Jack Mezirow who is acknowledged as the one who brought this topic to the forefront in his theories about adult learning talks about how adults structure meaning from experience. [11] Clark points out

> “these meaning systems function as a lens or filter through which personal experience is mediated and by which it is interpreted. While these structures organize our experience and make it coherent, they also distort perception to some degree by establishing what Mezirow calls “habits of expectation” that limit perception.”[10]

The point of transformative or transformational learning is to transform our perception by finding new meaning. It could be a very simple “aha” moment. It could be a transformational experience like your first optics job. It could just be a subtle shift in perception like a gestalt shift that enables you to understand things differently.

Another view of transformational learning is that given by Daloz[12] whose research focuses on undergraduate education. In his book Daloz discusses how change is affected through the mentoring process. Quoting Clark, “Daloz’ goal is to challenge teachers to think about their teaching not so much in terms of developing competencies but rather in terms of fostering personal development.”[10]

Almost all the references I’ve read on transformational learning stress reflection as part of the process of developing meaning. Some discuss techniques of working in groups, some talk about students coaching one another, and others stress the mentoring process. Transformational learning concepts have matured and trickled down into just about every level of education. Although these techniques are not as prevalent in the science and engineering literature, I found a number of specific examples utilizing these techniques.[13-18]

One example is a paper titled “Teaching as Coaching: A case study of awareness and learning in engineering education.”[14] Gynnild et al. discuss education based on a “knowledge transfer model” and that “to be a successful teacher has often been equated to gaining high scores on presentation skills in student evaluation forms.” They interviewed students in a master’s level oceanography class. Students reported on their ways of studying and how they felt they were doing. This was compared to examination scores. Interviews after a midterm exam also became a coaching intervention that helped some students improve their study habits. They pointed out that there were some students who could do it on their own, while some students did best with a study partner. Others needed mentoring and coaching by the teaching assistant and significantly improved their grades. And, others did not assess their study habits as insufficient and did not take advantage of the learning opportunity. For this study it was left up to the students as to whether they took the opportunity or not. They found that when students become “deep learners” they are actively involved in learning and they strive to “develop higher levels of competence.”[14] However, some choose to remain “surface learners” and exert “as little effort as possible.” The methodology they developed for the deep learners was based on “action learning”[18] that “involves learning about learning for the purpose of further learning.”
Another study discusses the process of learning educational technology for teacher professional development as a means of transformational learning.[15] As the teachers learn about the technology that their students are already intimately familiar with it changes the way they teach and by inference the way they interact with their students.

In the field of optics there is an interesting study titled “Addressing student difficulties in applying a wave model to the interference and diffraction of light.”[17] We've all been through learning these concepts and likely been confused by some concept. The methodology addresses some specific means to demonstrate through laboratory exercises the basic concepts of interference and diffraction. The subjects were students as well as the teaching assistants mentoring the laboratory sessions. Both groups were tested on basic concepts before and after the exercises. The goal was to get the teaching assistants up to speed quickly and have them be able to then teach the students to master the concepts. This interactive, hands on, mentored paradigm proved to be effective. Although not 100% effective, student scores rose from 25-40% pretest to 65-80% post test on various concepts.

Even though many of the studies I found did not refer to transformational learning, the techniques they used were applying many of the basic concepts and the results did change the learners.

4. DISCUSSION

So why am I bringing this up? I believe that unless a topic has some meaning to a student it isn’t going to stick. They retain what they want to retain. If they don’t think it’s useful they don’t recall it. I constantly remind my students of things they’ve learned in one or more other classes. But because they didn’t have a meaningful context for it, they say they don’t recall. Once they have a meaningful context for it, they remember it.

Another aspect of this from my perspective is that throughout the basic and intermediate undergraduate courses the expectations are to learn the information. When they take more advanced classes, especially when they are seniors, they are applying this information and beginning to discern what it is they want to pursue after they graduate. Will it be a job or graduate school? Most first semester seniors really have not decided what they want to do. A few know, but most don’t. Also we want our graduating students to have the skills they will need for either a job or graduate school. They need to be able to put together a presentation. They need to be able to research a topic either to find out how to do something, or to be able to make a decision that may affect the company they work for. They also need to learn to work in teams and on larger projects. At the University of Arizona we have a senior capstone engineering project where interdisciplinary teams solve real world problems for a sponsor company or research lab. As I have watched students go through this process it is truly transforming to them. They grow in many ways doing these projects.

For the last 4 years I have been teaching a first semester senior level required optical engineering in optical fabrication and testing at the University of Arizona. There is a long list of topics to be covered in this class and as in most classes it’s not possible to cover every single topic in depth. Instead I make a list of the core topics that need to be covered with some additional and often hot topics related to fabrication and testing. I have the students work in teams of 2 and have them choose what topics they want to teach the class. From this list I put together the plan for the semester. Each team of 2 prepares a PowerPoint and handouts based on readings from the current literature I give the students. If they want mentoring I make myself available. By the end of the semester every student has stood in front of the class and presented a topic. After each topic we have a discussion on that topic. I use the Socratic method of asking questions a lot in my classes and ask students to come up with different ways of doing the same kind of test or asking tradeoffs in different types of fabrication. So many of them have had jobs where they’ve worked on these things that they can bring their experience into the classroom and their classmates learn from them. In the real world we most often learn when we mentor or teach another and that is why I foster this type of approach.

Another key aspect of my class is that each student chooses a research topic that has to do with making or testing some type of optical component or system. It can be anything from contact lenses to LCD displays, from laser hair removal to giant telescopes. The point is they choose what they want to learn about. I coach them through the steps of choosing a topic, doing research, organizing their material and writing a coherent scientific paper. I read and comment on any draft a student wants to give me. Some students just hand in the final paper. Others really want to keep polishing it until they have achieved a publishable paper. At the end of the semester I find I learn a lot from what they present in their papers. Some students figure out what they want to do once they graduate by going through this process. A totally undecided, uninterested student can all of a sudden become extremely interested in something and they are transformed as they realize that this is what they want to do.
Although these observations and comments are not the result of a scientific study, the results are noticeable to me. And, I’ve found it’s much more fun teaching this way. Yes, it takes more preparation on my part because each year what we cover is different. Yes, it takes more time working one on one with students when class sizes are 35-40 students. But to me it’s more rewarding for everyone.

5. CONCLUSIONS

Does this help answer the “what is” questions? Does this help me answer my colleagues questions? Well, maybe, but not necessarily. It does get me thinking reflectively about concepts and methodology. About how there is no one answer. All I can do is to discuss the prevalent theories and what the possible implications are as well as other means of explaining the same observations. We can’t get stuck on a supposed “fact” like the speed of light because now we’ve seen results of experiments where light was sped up, light was slowed down, or even more intriguing, frozen light.

So even if we can’t answer the questions, we can keep asking the questions. The process we go through in sharing our theories and observations with one another will change the course of our knowledge over time. We do influence one another in these encounters. And we all learn there are other possibilities we haven’t considered.

What about how we teach optics? I suggest coaching and mentoring students and young colleagues as much as you can to help them learn how to transform their interpretations and meanings. Help them develop critical thinking and look at different possible explanations for what they’re observing to develop the ability to solve new problems in creative and scientific ways. Foster more small group discussion on the “what is” questions. The more we can shift the learning paradigm the more transformational learning we can experience.

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