

Student Descriptions of Refraction and Optical Fibers

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Abstract. This paper reports our research into how students describe and think about optical fibers and the physical phenomena of refraction and total internal reflection (TIR) basic to their operation. The study was conducted as part of the improvement and expansion of web-based materials for an innovative Rensselaer introductory physics course¹ that examines the physics underlying information technology. As we developed the prototype module, we examined students' understanding of the phenomena of refraction, TIR, and optical fibers through the use of clinical interviews. As students discussed refraction and tried to explain how optical fibers work, several patterns emerged. Our analysis of these patterns drives our assessment of the effectiveness of the revised materials in facilitating students' transfer of learning, as well as the development of a multiple-choice diagnostic tool.

¹Materials found at <http://www.rpi.edu/dept/phys/ScIT/>

INTRODUCTION

The Science of Information Technology (ScIT) is an innovative introductory course that connects physics with technological contexts of interest to today's students. For example, in ScIT we apply total internal reflection (TIR), a phenomenon commonly covered in traditional physics courses, to optical fibers, a technology eminently relevant to the students. This study is part of the expansion and improvement of ScIT's web-based materials [1] to facilitate their widespread dissemination.

Part of our ongoing development process is to assess student preconceptions associated with different levels of comprehension. The Physics Education Research (PER) literature abounds with studies of preconceptions [2], but few studies have examined how students approach the topics that form the backbone of ScIT: *e.g.*, total internal reflection (TIR) and semiconductor physics. Like many before us [3-6], we used clinical interviews to open a window into student understanding of our target topics – optical fibers, refraction, and TIR. In this paper we discuss our categorization of responses, based on 41 interviews with subjects of diverse physics backgrounds.

METHODOLOGY

In the summer of 2002, we conducted face-to-face (f2f) interviews with Group A, a convenience sample of five in-service teachers, four physics majors, an engineering major, and two physics faculty. These interviews provided a “broad picture” of how individuals think about optical fibers. The following spring, we conducted pre-instruction “e-interviews” with Group B, all 22 ScIT students, followed by post-instruction e-interviews with 8 of those 22. (We chose to e-interview using Chat Rooms on WebCT, since timing and location made f2f interviews impossible. A comparison of the two formats is found in ref. [7].) One pre-interview was incomplete; Table 1 displays the physics backgrounds of the remaining 33 subjects.

All interviews were conducted by the same interviewer (a physicist); many were observed by a cognitive psychologist to gauge their efficacy. Interviews began with participant identification and verification of informed consent. Subjects were then asked, “What does an optical fiber do?” As we probed further, our choice of questions was driven by student responses and included “How might the fiber keep the light from escaping?” “What can you tell me about refraction?” and “How does Total Internal Reflection occur?”

TABLE 1. Physics Background of Interviewees.

Highest Completed Physics Course	Grp A	Grp B
High School Physics	1	9
College Physics I	0	8
College Physics II	4	3
Upper-Level Coll. Phys.	5	1
Physics Faculty	2	0

We examined the video recordings and transcripts¹ from the 41 interviews for patterns and progressions. We grouped similar student descriptions and drafted network schematics (*e.g.*, Fig. 2). Schematics were roughly outlined at first, then refined to include all interviewee accounts.

RESULTS AND ANALYSIS

Descriptions of refraction, TIR, and optical fibers were as varied as the students providing them. No categorization scheme can completely encompass the diversity, but we have identified some themes. Through this process, we found that optical fibers and refraction needed separate groupings. In hindsight the separation is not surprising. Optical fibers are a technology, and student descriptions fall along a single progression from novice to expert. Whereas refraction and TIR are physical phenomena, and students approach them from a variety of starting points. The following analyses reflect these differences.

Optical Fibers

All interviewees had heard of optical fibers or fiber optics, but few could correctly describe how they worked. We grouped student responses into five “stages,” numbered from 5 to 1 according to how close the descriptions were to the “expert” descriptions comprising Stage 5. The stages (and sub-stages) are listed in Table 2 and described below.

Stage 5: Accurate models identify TIR with optical fibers and correctly describe how TIR arises from the bending of light at a boundary between two media.

Stage 4: Incomplete refraction models tie the operation of fibers to refraction but are not complete. Descriptions in Stage 4B indicate that the indices of refraction factor into the operation of an optical fiber, but they do not fully explain how TIR works. Responses in Stage 4C rely upon Snell’s Law and TIR but are not entirely correct. *E.g.*, they say TIR will

¹ Capitalizations and misspellings have been corrected in excerpts of the e-interview transcripts presented here. “...” represents non-essential comments by either interviewee or interviewer.

TABLE 2. Number of Descriptions in Each Stage Categorization. Subjects moving between stages during an interview are counted in their initial stage.

Stage Sub-Stage	1	2	3				4			5
			A	B	C	D	A	B	C	
Group A	2		1		3				1	5
Group B Pre	3	2	2	4	5		1	1	2	1
Group B Post						1		1	3	3

occur when light leaves a rarer medium and enters a denser medium. Only one subject suggested refraction as a means to guide light without discussing TIR (Stage 4A). When asked what kept light from escaping the sides of a fiber toy he had previously described, subject B10 replied, “OK, well I would assume that the light was modified some way, either refracted or directed in such a way that keeps the light contained.”

Stage 3: Reflective models involve light reflected off the sides of the fibers but make no mention of refraction’s role. Stage 3A responses involve the placement of tiny mirrors within the fiber at strategic locations, such as where the fiber must bend. Those in Stage 3B coat the entire inner fiber with a silvered surface. Descriptions in Stage 3C involve reflection from an unspecified coating. Subjects in Stage 3D face a quandary. They realize (generally from having seen a fiber) that the walls are not silvered, but they cannot come up with another way to guide light.

Stage 2: “Containment” models involve the use of an opaque, but not necessarily reflective, coating to keep light from escaping the fiber. This model was the starting point for two subjects; three others entertained this model during their interviews, as seen in Fig. 1.

Stage 1: Unique models lack the information that optical fibers carry data in the form of a beam of light. The six descriptions in this category are very different from each other; here are two examples.

A5: “An optical fiber ... filters [incoming] particles out to make their sight or sound or whatever Optical meaning light, so I am assuming that it’s light particles being broken up and then kind of reassembled. With higher resolution - perhaps these fibers help create better resolution.”

B17: “[An optical fiber is] a type of wire connection that uses fibers to make it faster. ... Inside the wire there is a type of fiber substance around the wire that helps in the moving of electrons like in TV fiber optics. ... Optics deals with sight, so the optical fibers find a way to maximize the speed of electrons with refractors in the fibers to display for sight. ... I’m guessing the fibers are made of small mirrors that are attached to insulators in the wires.”

Subjects moved between stages in 9 of the 41 interviews. This movement is summarized in Fig.1. Movement between stages during an interview was more common in the convenience sample (Group A) interviews because the interviewer did not have to worry that instruction in the interview would corrupt future post-instruction analysis. For example, subject A6 was told that “Optical fibers ... carry transatlantic communication How do you think something might be made that ... makes light go the whole distance?” This information helped A6 move from Stage 1 to 3D.



FIGURE 1. Movement between stages. Nine interviewees moved between stages. Subject B20 did not change from one stage to another but put forth two models without choosing between them.

Subject A7 illustrates how interviewees moved between Stages 2 and 3 as they thought about optical fibers. He started in Stage 3C: “From what I understand, it’s ... a series of reflections.” He next shifted to Stage 3D by rejecting mirrors: “... I think just by a series of ... I don’t want to say mirrors, but it’s got to be ... a mirror-like substance ... it can’t be glass ’cause it’s flexible.” He visited Stage 2: “maybe it wouldn’t need to reflect ... you can’t escape the, the insulator, right? ... maybe it can just, shwooo, travel right through. ... it’s a plastic substance, I know, ’cause they use it for ... that cable for computers and things.” A7 finally ended back in a quandary (3D): “I don’t know how you would do it. ... it’s gotta be reflecting somehow. I don’t know.”

The eight post-instruction interviewees were among the weaker students in the class (they agreed to the interview for extra credit at the end of the semester), yet each (to our relief) provided a more expert description than in the pre-instruction interview. The most significant transition was for subject B6, who moved from Stage 1 at the start of the course to Stage 5 in the post-interview. The least change was seen in subject B4. He started the semester in Stage 3C; at the start of the post-interview, he appeared to be in Stage 3D: “I don’t believe [the fiber] is coated with a mirror but a material that reflects the light like a mirror...can’t recall exactly.” When questioned about refraction and TIR, however, this student invoked fiber terminology,

apparently moving into Stage 4C: “The critical angle is the two indexes of refraction inside the core ... [When light strikes the surface at less than the critical angle] it is completely reflected within the fiber.”

Interviewees who correctly explained optical fibers seemed able to draw upon three key principles: (I) Fibers carry information in the form of a coherent beam of light; (II) Mirrored surfaces are not suitable;² and (III) Light can be guided using refractive effects, such as TIR. Subjects in Stages 1 or 2 lack cognizance of I – they have no concept of how data is carried by light. Students in Stages 3A and 3B, and possibly 3C, surmise that fibers rely on mirrors. When they recognize II but not III, they end up in a quandary (Stage 3D) because they can think of no other method to guide light. The ability to correctly apply refraction to the guidance of light distinguishes Stages 4 and 5.

The disconnect between Stages 3 and 4 appears significant. Many subjects deduced principles I and II from having seen optical fibers, but principle III seems difficult to discover without explicit instruction. All interviewees above Stage 3, with the possible exception of B10, had previously “heard” that fibers work through refraction. Explaining that fibers carry a signal in a beam of light could prompt movement from Stage 1 or 2 into Stage 3, but not Stage 4. Even some subjects who knew about TIR appeared to view reflection and refraction as incompatible phenomena. A6 described the TIR ray as “refracted so much that it’s actually refracting into ... the fiber,” its direction given by Snell’s Law rather than the law of reflection.

Refraction

Refraction and TIR were explicitly discussed in 8 Group A interviews and 21 Group B interviews.³ The term “refraction” was familiar to each of these interviewees, and all but five connected it to the bending of light. Yet subjects evinced diverse approaches to refraction and TIR, drawing upon a variety of resources to explain the phenomena.

Figure 2 illustrates the connections made by interviewees. The goal was a correct explanation of TIR – either by using Snell’s Law or through a more conceptual description; experts provided both. Critical to either description is the concept that light bends. Stu-

² Students in Stage 3D generally reject mirrors because they’ve seen fibers (e.g., character toys and computer cables) and remember the flexibility and/or absence of a silvered surface. In contrast, faculty pointed out that mirrors absorb light, which makes them unsuitable.

³ Probing of refraction was constrained by the direction taken during the interview, the subject’s background, and time limitations.

dents drew upon specific applications of refraction and TIR, such as prisms, diamonds, and illusions like a pencil “broken” at the surface of water. Other resources, such as the equation for Snell’s Law and the association of refraction with a change in speed, were more technical.

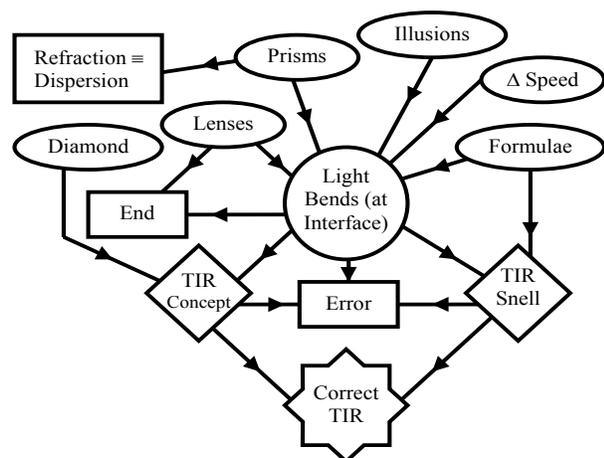


FIGURE 2. Conceptualization of refraction. Items in ovals are resources; rectangles surround dead-ends; and the other shapes represent correct conclusions. Arrows point from tool to conclusion, not always the order in which topics arose.

Knowing that wavefronts bend as they change speed seems essential to a conceptual explanation of refraction and TIR. All 11 subjects who connected a change in speed to refraction also recognized that the path of light bends, but not all who knew light bends mentioned a change in speed. When asked to explain TIR “to someone who doesn’t know what a sine function is,” subjects like A1 could not get past mathematics and definitions: “Total internal reflection is governed by a, uh, critical angle. ... A certain parameter, call it theta c, If you have a beam of light, um, at this critical angle, I think that will be the first point which you’re going to have total internal reflection.” But those interviewees who could correctly explain TIR by both qualitative and quantitative means started from the definition of index of refraction as a ratio of speeds when asked to explain TIR without sines.

Nine students related refraction to prisms; six of them did not differentiate refraction from dispersion. For example, when asked, “How does refraction work?” Subject B1 responded, “Light hits a material and then dissipates into its components based on the various wavelengths.” Subject B2 replied, “diffraction is when light passes through a prism and is split into different wavelengths, and refraction is light being recombined.” Understanding that bending and dispersion can occur independently evidently requires additional contrasting experiences.

IMPLICATIONS

Analysis of the interviews is influencing the development of ScIT materials in many ways. We have added a photograph of a toy using fibers to explicitly connect to students’ prior experiences. Each figure with a refracted ray now shows a reflected ray too, to discourage students from viewing reflection and refraction as mutually exclusive. To discourage students from equating dispersion with refraction, we have moved our dispersion discussion from the refraction module to a signal loss and distortion module. Diagnostic questions involving optical fibers now begin with the explanation that fibers carry information in the form of light pulses and incorporate descriptions from interviews. Subsequent studies with a larger sample, using multiple-choice questions as well as clinical interviews, are necessary to test the generality of these models, to refine our diagnostic tool, and to gauge how different instructional approaches affect students’ understanding of refraction, total internal reflection, and optical fibers.

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REFERENCES

1. All materials are web-based, and many can be found at the ScIT website: <http://www.rpi.edu/dept/phys/ScIT>.
2. See, for example, E. F. Redish and L. C. McDermott, “Resource Letter PER-1: Physics Education Research,” *Am. J. Phys.* **67** (9), 755-767 (1999).
3. E. Hunt and J. Minstrell, “A Cognitive Approach to the Teaching of Physics,” in *Classroom Lessons Integrating Cognitive Theory and Classroom Practice*, edited by K. McGilly (Cambridge, MA: MIT Press, 1994).
4. L.C. McDermott, “Research on conceptual understanding in mechanics,” *Physics Today*, **37** (7), 24-32 (1984).
5. I. A. Halloun and D. Hestenes, “Common sense concepts about motion,” *Am. J. Phys.* **53** (11), 1056-1065 (1985).
6. E. F. Redish and R. N. Steinberg, “Teaching Physics: Figuring Out What Works,” *Phys. Today* **52** (1), 24-30 (1999).
7. We report on the e-interview experience in D. Wagner, J. Rivera, F. Mateycik, and S. Jennings, “Using Electronic Interviews to Explore Student Understanding,” submitted to 2004 PERC Proceedings.