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THE NATURE OF KEY IDEAS IN TEACHING HIGH SCHOOL PHYSICS: THREE TOPICS IN OPTICS, *COLOR, THE SPEED OF LIGHT, AND LIGHT INTERFERENCE*

By

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ABSTRACT

THE NATURE OF KEY IDEAS IN TEACHING HIGH SCHOOL PHYSICS: THREE TOPICS IN OPTICS, *COLOR, THE SPEED OF LIGHT,* AND *LIGHT INTERFERENCE*

By

Zongyi Deng

The distinction between key ideas in teaching school science and key ideas in the disciplines of science is crucial and yet largely ignored in scholarly discourse about what science teachers should teach and what they should know. This dissertation seeks to clarify this distinction through investigating how and why the key ideas in teaching three topics in optics, *color*, *the speed of light*, and *light interference*, for high school students differ from the key ideas in teaching for prospective physicists or scientists.

This study employed Dewey's idea about *psychologizing subject matter* and Harre's theory of *referential realism* as theoretical underpinnings. It consists of 1) a case study of two experienced physics teachers; 2) a comparative analysis of the key ideas in teaching the three topics at the high school level and the key ideas in the discipline of physics; and 3) interviews with the two physics teachers and with two optics professors.

The study found that the key ideas in teaching the three topics for high school students differ markedly in theory types, source analogues, and representations from the key ideas in teaching for prospective physicists or scientists; and that the differences are determined by

differing purposes of teaching, knowledge backgrounds and experience of learners, and ways of selecting and formulating key ideas in textbooks.

This dissertation argued that not every idea in the discipline of physics can be taught to anybody of any age in a way that is intellectually honest to the discipline; that knowing the structures of the discipline of physics does not guarantee that physics teachers have the specific kind of subject-matter knowledge needed for teaching school physics; and that key ideas in teaching school physics constitute an essential component of pedagogical content knowledge.

This study calls for more empirical research on the nature of key ideas in teaching school science; development of a special subject-matter sequence for the education of science teachers; and development of a theoretical base for the construction of a science curriculum that bears a transparent relationship to the structures and development of science.

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CHAPTER 1

INTRODUCTION

This chapter first provides a discussion of the nature of the problem, followed by an explanation of the research questions and a review of literature. It next presents an description of the purpose and significance of the study. The chapter ends with an overview of the dissertation itself.

The problem

> [W]hat should we teach first? Should we teach the *correct* but unfamiliar law with its strange and difficult conceptual ideas, for example the theory of relativity, four-dimensional space-time, and so on? Or should we first teach the simple "constant-mass" law, which is only approximate, but does not involve such difficult ideas? The first is more exciting, more wonderful, and more fun, but the second is easier to get at first, and is a first step to a real understanding of the second idea. This point arises again and again in teaching physics. (Feynman, 1995, p. 3)

While what Richard Feynman addressed is primarily for teaching physics for prospective physicists or scientists, the question "what should we teach first?" is also a very crucial one in teaching science for elementary or secondary school students, as well as in the education of school science teachers.

In the discourse community of science education, what teachers should teach is believed to be centered around "key ideas" (or "basic ideas") that constitute the "structure" of a subject matter. The meaning of key ideas not only denotes what science teachers should teach, but also implies what science teachers should know in order to teach.

The first scholar who marked a landscape in the meaning of key ideas was Jerome Bruner through the phrase "structure" in his *The process of education* (Bruner, 1961). A structure is said to be constituted by the basic ideas (concepts, principles, or laws) that lie at the heart of a discipline. These basic ideas should be determined by distinguished scientists who work at the frontiers of their disciplines. Bruner (1961) believed that "intellectual activity anywhere is the same, whether at the frontier or in a third-grade classroom" (p. 14), and that "any subject can be taught effectively in some intellectually honest form to any child at any stage of development" (p. 33). Accordingly, from the perspective of Bruner, it is unnecessary to make a distinction between key ideas in teaching science for school students and key ideas in the intellectual disciplines of science.

Joseph Schwab was another scholar who set the meaning of key ideas in which others thereafter moved through the phrases "substantive structure" and "syntactic structure". A substantive structure is said to be constituted by the concepts or principles which play the role of guide to the inquiry in the disciplines of science. A syntactic structure is said to be formed by methods, canons of evidence, and warrantability in the inquiry (Schwab, 1964). Again, no explicit distinction is made between key ideas in the intellectual disciplines of science and key ideas in teaching science for school students. From Schwab's point of view, key ideas in teaching science for school students are drawn directly from the key ideas that compose the substantive and syntactic structures of the disciplines of science.

The phrase "structure" has not only shaped the meaning of what science teachers should teach, but also fashioned the discourse about what science teachers should know. It has been proposed that in order to teach a subject, teachers need to know about the substantive and syntactic structures of the academic discipline of that subject (see Shulman, 1986; 1987; Wilson, Shulman, & Richert, 1987; Grossman, Wilson, & Shulman, 1989; Wilson, 1988; & Grossman, 1990). But how does teachers' knowledge of the structures differ from the kind of understanding developed by subject-matter specialists? In teaching science at the elementary or secondary level, teachers are not scientists, but rather teachers of science. They need to understand the structures in the discipline <u>differently</u> than scientists do.[1] There is a lack of distinction between key ideas in teaching school science and key ideas in the discipline of science in

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[1] Kennedy (1989a) believed that teachers need to know subject-matter knowledge differently than others (e.g., mathematicians, scientists or historians).

scholarly discourse about what teachers should know.

The research questions

This study investigated the distinction between key ideas in teaching school physics and key ideas in the intellectual discipline of physics through addressing two questions:

1. How do key ideas in teaching school physics differ from those in the discipline of physics?

2. Why do key ideas in teaching school physics differ from those in the discipline of physics of physics?

By key ideas in teaching school physics, I mean the concepts or principles that are essential for school students of a particular age to understand a particular physics topic. By key ideas in the discipline of physics, I refer to the concepts or principles that are essential for scientists or physicists to understand that topic.[2] I believe it is very important to draw a distinction between key ideas in teaching school physics and key ideas in the discipline of physics. For one thing, key ideas in teaching school physics are usually different from key ideas in the

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[2] In this study, key ideas in teaching school physics or in the intellectual discipline of physics are more about the substantive dimension of knowledge (Schwab, 1964). Although I focus on the substantive dimension of key ideas, I also examine the syntactic dimension of key ideas (Schwab, 1964) through addressing an epistemological issue: how are key ideas formulated or developed? Indeed, Phillips and Soltis (1991) argued that the substantive and syntactic dimensions of knowledge are inseparable.

discipline of physics. *Newton's 2nd law* for high school students can be stated as "The change in motion of an object is proportional to the applied force and inversely proportional to the mass" (AAAS, 1993, p. 91) and can be represented by "F=ma". In the discipline of physics, *Newton's 2nd law* can be stated as "the time-rate-of-change of a quantity called momentum is proportional to the force" and can be represented by "F=d/dt P" (Feynman, Leighton, & Sands, 1989, p. 9-1). By using the concept "the time-rate-of-change of momentum" or the equation "F=d/dt P", the meanings of *Newton's 2nd law* in the discipline have been qualitatively transformed as well as quantitatively enriched.[3] For another, as I will discuss in the following, key ideas in teaching school physics are a form of pedagogical content knowledge that can set physics teachers apart from non-teaching physicists.

Key ideas in teaching (school physics) and pedagogical content knowledge

My assumption that key ideas in teaching (school physics) constitute a component of pedagogical content knowledge is supported by Shulman & Sykes (1986) and Prawat (1989a; 1989b). Shulman & Sykes (1986) believe that

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[3] "F=ma" can only applied the objects whose velocities must be small compared with the velocity of light and whose masses must be constant. "F=d/dt P" are applicable to the objects whose velocities can be near to the velocity of light, and whose masses can be in constantly change.

pedagogical content knowledge involves an understanding of key ideas (core concepts, skills, and attitude) which are essential in teaching students of a particular grade level, an understanding of students' learning difficulties or preconceptions, and an understanding of pedagogical representations:

> understanding the central topics in each subject matter as it is generally taught to children of a particular grade level and being able to ask the following kind of questions about each topic: What are core concepts, skills and attitudes which this topic has the potential of conveying to students?....What are the aspects of this topic that are most difficult to understand for students? What is the greatest intrinsic interest? What analogies, metaphors, examples, smiles, demonstrations, simulations, manipulations, or the like, are more effective in communicating the appropriate understandings or attitudes of this topic to students of particular backgrounds and prerequisites? What students' preconceptions are likely to get in the way of learning? (p. 9)

Prawat (1989a) believed that key ideas in teaching a given topic to students at a particular age are a substance of pedagogical content knowledge. He argued that key ideas in teaching possess the potential of promoting the accessibility of content to learners (Prawat, 1989b).

However, my examination of empirical research of pedagogical content knowledge in science and in other subject areas reveals that few studies have been done to investigate the nature of key ideas in teaching as a component of pedagogical content knowledge. Most research concentrates on examining three other components of pedagogical content knowledge: pedagogical representations, instructional strategies, and students' preconceptions. Let's take a close look at three empirical studies about science teachers' pedagogical content knowledge (i.e., Smith & Neale, 1989; Geddis, Onslow, Beynon, & Oesch, 1993; Clermont, Borko, & Krajcik, 1994).

One of the purposes of Smith & Neale's (1989) study was to document the pedagogical content knowledge ten primary teachers brought with at the beginning and how their knowledge changed as they participated in a summer program that focused on conceptual teaching. Smith & Neale defined *pedagogical content knowledge* as "translation and interpretation of content during teaching" which included 1) *strategies for teaching content* ("eliciting students' preconceptions and predications about phenomena," "asking for clarification and explanation," "providing discrepant events," "encouraging debate and discussion about evidence," and "clearly presenting alternative scientific explanations"); 2) *shaping and elaborating the content* ("the teacher's use of examples, good explanations, metaphors, analogues, and representations"). Through interviewing and videotaping of the teaching of two science topics, "light" and shadow," and having teachers keep reflection logs, Smith & Neale showed that few teachers possessed knowledge of students' concepts, knowledge of conceptual change teaching strategies, and knowledge of examples and representations for the topics at the time they came to the program. They also showed that as teachers began to develop knowledge of students' concepts in the program, three teachers made significant progress in their use of the conceptual change teaching strategies.

Geddis, Onslow, Beynon, & Oesch (1993) explored the "unity" of pedagogical content knowledge through investigating the teaching of "isotopes" at the high school level conducted by two student teachers. They defined pedagogical content knowledge as "knowledge that plays a role in transforming subject matter into forms that are more accessible to students". This knowledge includes "student misconceptions," "strategies for altering misconceptions," and "alternative representations." Based upon field notes of their classroom teaching, and audio-recorded and transcribed interviews with the two student teachers and their cooperating teachers, Geddis et al. articulated four categories of pedagogical content knowledge: "learners' prior knowledge," "effective teaching strategies," alternate representations of the subject matter" (models, analogies, examples, and demonstrations), and "curricular saliency" that was about "the importance of various topics related to the curriculum as a whole" (p. 588).

The purpose of Clermont, Borko, & Krajcik's (1994) study was to investigate the nature of pedagogical content knowledge of experienced and novice science teachers with respect to a single teaching strategy, demonstration teaching. They defined pedagogical content knowledge as "a blend of content and pedagogy that provides teachers with an understanding of how particular subject matter topics, problems, and issues are organized, represented, and adapted to the diverse interests and abilities of learners, and then presented for instruction" (p. 419). Seven novice and five experienced teachers participated in the study. Clermont, Borko, & Krajcik (1994) first showed each teacher two videotaped demonstrations, and then conducted a clinical interview (including a think-aloud, critical-stop task, and a follow-up semi-structured interview) to elicit his/her pedagogical content knowledge with respect to the demonstration teaching of two basic concepts in chemistry, "density" and "air pressure". They found that experienced teachers possessed a much broader and richer set of mental representations for demonstrating the two topics, and demonstrated greater ability to critique videotaped demonstrations than novice teachers did.

Evidently, researchers in these three studies tended not to treat key ideas in teaching--both conceptually and empirically--as a component of pedagogical content knowledge.[4] Examination of empirical research in other

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[4] It is worth pointing out that key ideas in teaching haven't received attention in empirical studies about science teachers' content knowledge as well. Most research concentrates on unveiling science teachers' in-depth disciplinary understanding of a particular topic in science,

subject areas also indicates this trend. Researchers concentrated their investigation on pedagogical representations (e.g., analogies, examples, models, metaphors) (e.g., Wilson, Shulman, & Richert, 1987; Ball, 1988; Barnett, 1990; Marks, 1991); instructional strategies (e.g., lecture, discovery teaching, conceptual change teaching) (e.g., Wilson, Shulman, & Richert, 1987; Barnett, 1990; Marks, 1991), or students' preconceptions (e.g., Carpenter, Fennema, & Peterson, 1988).

The failure of conceptualizing key ideas in teaching as a component of pedagogical content knowledge would lead to a flawed assertion that school teachers represent key ideas in a academic discipline to elementary or secondary school students through employing pedagogical content knowledge (i.e., mainly alternative representations)--again, a confusion of key ideas in teaching a school subject with key ideas in a scholarly discipline. In a critique of the idea of pedagogical content knowledge,[5] McEwan & Bull (1991) interpreted pedagogical content knowledge as a command of

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rather than science teachers' understanding the topics in a context of teaching it to students of a particular age. (e.g., Carlsen, 1987; 1988; Hashweh, 1985; Smith & Neale, 1989; Tobin & Carnett, 1988; Happs, 1987; Tobin, 1987)

[5] On epidemiological grounds, McEwan & Bull (1991) rejected Shulman's idea based upon through concluding that it is unnecessary and untenable to distinguish content from pedagogical content knowledge. This critique is absurd because they had misinterpreted and misrepresented the idea of pedagogical content knowledge (PCK itself has an inseparable content component).

alternative representations and special skills in selecting and adapting these representations. Accordingly, they perceived the criterion for distinguishing teachers from scholars as that teachers are capable of representing scholarly subject matter (or key ideas in the scholarly disciplines) to young students through alternative representations and scholars aren't.

The significance of this study

This study seeks to clarify the distinction between key ideas in teaching school science and key ideas in the scholarly disciplines of science through describing and explaining the differences between the key ideas in teaching certain physics topics for high school students and the key ideas in teaching the same topics for prospective physicists or scientists. This distinction, as already illustrated, is very crucial and yet largely ignored in scholarly discourse about what science teachers should teach as well as what science teachers should know. By focusing on investigating this distinction, I believe this study could be a significant contribution to our understanding of what science teachers should teach and what science teachers should know. More specifically, this study had the potential of addressing three issues which evolved--explicitly and implicitly--from above discussion of the problem:

1) Can any idea in the intellectual discipline of

physics be taught to anybody of any age?

2) Is knowing the structures of the academic discipline of physics sufficient for physics teachers to teach school physics?

3) In what sense do key ideas in teaching school physics constitute a component of pedagogical content knowledge?

An overview of the dissertation

The dissertation contains seven chapters. Chapter one provides an introduction of the study problem and the research questions.

Chapter two develops a conceptual framework which is based upon Dewey's idea about *psychologizing subject matter* and Harre's theory of *referential realism*.

Chapter three is about the design of this study. It includes three components: 1) a case study of two high school experienced physics teachers; 2) a contrast of the key ideas in teaching the three topics, *color*, *the speed of light*, and *light interference*, at the high school level with the key ideas in the discipline; and 3) interviews with the two physics teachers and two optics professors.

Chapter four presents the findings about the key ideas in teaching the three topics based on the case study of the two experienced physics teachers.

Chapters five provides the findings about how the key ideas in teaching the three topics at the high school level differ from those in the discipline of physics.

Chapter six develops an explanation of why the key ideas in teaching *color, the speed of light*, and *light interference* at the high school level differ from those in the discipline, in light of purposes of teaching, knowledge background or experience of learners, and ways of selecting and formulating key ideas in textbooks.

In chapter seven, this dissertation concludes with establishing three claims and discussing their implications for research on science teachers' pedagogical content knowledge, science teacher education, and construction of a science curriculum.

Chapter 2

A CONCEPTUAL FRAMEWORK

The main purpose of this dissertation study, as I have indicated, is to investigate the nature of key ideas in teaching school physics through describing and explaining the differences between key ideas in teaching school physics and key ideas in the intellectual discipline of physics. Why do key ideas in teaching school physics differ from those in the discipline of physics? What might account for the differences between key ideas in teaching school physics and key ideas in the intellectual discipline of physics? How can I describe, interpret, and compare key ideas in teaching school physics and in the discipline of physics?

To address these questions, I discuss the theoretical underpinnings of the dissertation: Dewey's idea about *psychologizing subject matter* and Harre's theory of *referential realism*. I first examine Dewey's idea about *psychologizing subject matter*. Two propositions about why key ideas in teaching school physics differ from key ideas in the discipline of physics are developed from this examination. Next I discuss Harre's theory of *referential realism* to derive two propositions about different types of scientific theories and their ways of theorizing. Finally, I argue that these four propositions constitute a useful conceptual framework that enable me to describe, interpret, compare, and explain the differences between key ideas in teaching school physics and key ideas in the intellectual discipline of physics.

Dewey's idea about *psychologizing subject matter*

Why do key ideas in teaching school physics differ from those in the discipline of physics? To address this issue, I examined Dewey's idea about *psychologizing subject matter*. Dewey was the first scholar who made a distinction between subject-matter knowledge for a science teacher and subject-matter knowledge for a scientist. In "The Child and the Curriculum," Dewey (1902) wrote,

> Every study or subject thus has two aspects: one for the scientist as a scientist; the other for the teacher as a teacher. These two aspects are in no sense opposed or conflicting. But neither are they immediately identical. For the scientist, the subject-matter represents simply a given body of truth to be employed in locating new problems, instituting new researches, and carrying them through to a verified outcome. To him the subject-matter of the science is self-contained. He refers various portions of it to each other; he connects new facts with it. He is not, as a scientist, called upon to travel outside its particular bounds; if he does, it is only to get more facts of the same general sort. The problem of the teacher is a different one. As a teacher he is not concerned with adding new facts to the science he teaches; in propounding new hypotheses or in verifying them. He is concerned with the subject-matter of science as representing a given stage and phase of the development of experience. (pp. 200-201)

According to Dewey (1902), subject-matter knowledge for a science teacher should entail the "psychological aspect of experience." This aspect stands for subject matter in relation to learners. It reflects the historic development of subject matter. It "follows its [subject matter] actual growth; it is historic; and notes steps actually taken, the uncertain and tortuous, as well as the efficient and successful" (pp. 197). Subject-matter knowledge for a scientist, on the other hand, represents the "logical aspect of experience." This aspect stands for scholarly subject-matter knowledge which is characterized by a body of "finished" outcomes. It "neglects the process and considers the outcomes. It summarizes and arranges, and thus separates the achieved results from the actual steps by which they were forthcoming in the first instance" (pp. 197).

Subject-matter knowledge for a science teacher results from psychologizing subject matter--that is, translating scholarly subject-matter knowledge into forms that are within the experiential world of learners of a given age, and that can foster their growth toward mastery of that subject matter. As Dewey wrote,

> ....His [the teacher's, added] problem is that of inducing a vital and personal experiencing. Hence, what concerns him, as teacher, is the ways in which that subject may become a part of experience; what there is in the child's present that is usable with reference to it; how such elements are to be used; how his own knowledge of the subject-matter may assist in interpreting the child's needs and doings, and determining the medium in which the child should be placed in order that his growth may be properly directed. He is concerned, not with the subject-matter as such, but with the subject-matter as related factor in a total and growing experience. Thus to see it is to psychologize it. (pp. 201)

Furthermore, Dewey (1902) believed that psychologizing is characterized by two translations--a translation into the experience from which subject matter is derived, and a translation into the experience which is meaningful for and can be experienced by the child:

> Hence the need of reinstating into experience the subject-matter of the studies, or branches of learning. It must be restored to the experience from which it has been abstracted. It needs to be *psychologized;* turned over, translated into the immediate and individual experience within which it has its origin and significance. (pp. 200)

As a special kind of subject-matter knowledge for a physics teacher, key ideas in teaching school physics should represent the psychological aspect of experience. Key ideas in the intellectual discipline of physics, on the other hand, stand for the logical aspect of experience. Since key ideas in teaching school physics or key ideas in the discipline of physics refer to the fundamental concepts and principles that constitute the structure of subject matter, I distinguish between the psychological structure of subject matter--that is represented by key ideas in teaching school physics--and the logical structure of a subject matter--that is represented by key ideas in the discipline, in corresponding to the psychological and logical aspects of experience. This constitutes the first proposition of the conceptual framework.

What might account for the differences between key ideas in teaching school physics and key ideas in the intellectual discipline of physics? Knowledge background of learners is perhaps the most fundamental factor. It determines that the kinds of ideas (concepts or principles) in school teaching and the ways of organizing these ideas are distinguished from those in the scholarly discipline. Dewey (1916) explained,

> In fact, there are certain features of scholarship or mastered subject matter--taken by itself--which get in the way of effective teaching *unless* the instructor's habitual attitude is one of concern with its interplay in the pupil's own experience. In the first place, his knowledge [scholarly subject matter, added] extends indefinitely beyond the range of the pupil's acquaintance. It involves principles which are beyond the immature pupil's understanding and interest. In and of itself, it may no more represent the living world of the pupil's experience than the astronomer's knowledge of Mars represents a body's acquaintance with the room in which he stays. In the second place, the method of organization of the material of achieved scholarship differs from that of the beginner. (pp. 183)

Furthermore, knowledge background or experience of school students provides a referent for a science teacher in "psychologizing" the subject matter (or ideas) into a special kind which can be experienced by the students. As Dewey (1902) wrote,

> [W]hat concerns him, as teacher, is the ways in which that subject may become a part of experience; what there is in the child's present that is usable with reference to it; how such elements are to be used....He is concerned not with subject matter as such, but with the subject matter as a related factor in a total and growing experience. Thus to see it is to psychologize it. (pp. 197-201)

Another factor determining that key ideas in teaching school physics differ from key ideas in the intellectual discipline of physics is purposes of teaching. Why we teach physics has an influence on what we believe about key ideas. For the purpose of having school students develop a kind of in-depth conceptual understanding in physics, an instructor may emphasize teaching those concepts or principles that constitute the building blocks of the discipline. In this case, key ideas in teaching are more akin to the key ideas in the discipline. However, for the purpose of having students appreciate and interpret the natural phenomena in their daily living, an instructor would concentrate on teaching those concepts or principles which enable the explanation of a variety of natural phenomena. If this is the case, key ideas in teaching school physics might depart greatly from those in the discipline. Purposes of teaching, thus, imply the criteria for determining what ideas are important in teaching physics.

The last factor I examine here, curriculums or textbooks, appears to be less obvious. However, no matter whether teaching physics for prospective physicists or for high school students, textbooks occupy a very special place in determining and influencing what key ideas are and how these ideas are formulated. In the education of physicists or scientists, textbooks are the base from which they learn to practice their trade (Kuhn, 1970). What textbooks represent are more akin to the logical structures of the subject matter. They only record "finished" scientific achievements. The basic concepts or principles prospective physicists need to know for a particular area (e.g., optics) are summarized in a very precise, logical, and systematic form through textbooks. For this typical role played by textbooks in the education of physicists or scientists, Thomas Kuhn (1970) offered a very insightful account which is worth a lengthy quote:

> ....In these fields [contemporary natural sciences, added] the student relies mainly on textbooks until, in his third or fourth year of graduate work, he begins his own research. Many science curricula do not ask graduate students to read in work not written specially for students. The few that do assign supplementary reading in research papers and monographs restrict such assignments to the most advanced courses and to materials that take up more or less where the available texts leave off. Until the very last stages in the education of a scientist, textbooks are systematically substituted for the creative scientific literature that made them possible. Given the confidence in their paradigms, which makes this educational technique possible, few scientists would wish to change it. Why, after all, should the student of physics, for example, read the works of Newton, Faraday, Einstein, or Schrodinger, when everything he needs to know about these works is recapitulated in a far briefer, more precise, and more systematic form in a number of up-to-date textbooks? (pp. 165)

Like textbooks in the education of physicists, physics textbooks for school students also specify what ideas students need to know for each unit or chapter (cf, *Merrill physics* and *Conceptual physics*). A school text is an important resource for a physics teacher to know about what key ideas are, and how these key ideas should be represented or formulated in teaching a particular topic to students at a certain grade level. Lee Shulman (1986; 1987) argued that textbooks are the "pharmacopeia" from which a teacher draws key ideas, pedagogical representations, and instructional sequences. Leinhardt & Smith (1985) believed that textbooks provide an important resource for mathematics teachers to identify mathematical principles and procedures, pedagogical representations, and common students' errors and difficulties in teaching a particular topic for elementary students.

A school physics text is written for students of a particular age. The selection and formulation of key ideas are often adapted to the knowledge background or experience of the students. Therefore, in some degree, key ideas in a high school text have been "psychologized" to high school students. They are more akin to the psychological structures of the subject matter as compared to the key ideas in a college text for prospective physicists or scientists.

In what sense do the key ideas in high school physics texts represent the psychological structures of the subject matter as compared to the key ideas in college texts for prospective physicists or scientists that stand for the logical structures? Examining this issue, I believe, can enhance our understanding of why key ideas in the teaching of school physics differ from those in the intellectual discipline of physics.

It is important to keep in mind that any physics textbook is authorized by individual persons, a group of people, commission, or task force within a cultural context. A textbook doesn't determine what key ideas are, but the authors of these textbooks do. The selection and formulation of topics or key ideas in a text might reflect some sort of inherent beliefs, values, or consensus of the culture. An awareness of the influence of the cultural context within which the text is enacted is needed for a proper understanding the influence of a textbooks on the nature of key ideas.

It is equally important to keep in mind that like teaching practice in any other subject, physics teaching exists within a cultural context which may influence how an instructor thinks about the purposes of teaching, about the role of knowledge background or experience of learners, and about the role of textbooks in teaching. On the other hand, what an instructor believes about purposes of teaching, about the role of knowledge background or experience of learners, and about the role of textbooks may reflect the kinds of beliefs, assumptions, and values inherent in that culture. Again, being aware of the influence of cultural context within which teaching practice occurs is needed for understanding what key ideas are and how key ideas are formulated.

Taken together, I derive the second proposition for this study: within a cultural context, purposes of teaching, knowledge background or experience of learners, and textbooks, each in a certain degree, determine the nature of key ideas in teaching school physics and in the discipline of physics (i.e., teaching physics for prospective physicists or scientists). Accordingly, an examination of these three factors allows me to explain why key ideas in the teaching of school physics differ from those in the intellectual discipline of physics.

The above two propositions are centered upon why key ideas in teaching school physics differ from those in the discipline of physics. They are developed primarily based upon Dewey's idea about *psychologizing subject matter*. However, Dewey's idea alone is insufficient for addressing how key ideas in the teaching of school physics differ from those in the discipline of physics. Dewey didn't provide a theoretical explanation about scientific knowledge and scientific practice in his writing about psychologizing subject matter of science. What are the structures of scientific knowledge? How is scientific knowledge formulated? These are two epistemological issues essential to the idea about psychologizing subject matter of science, both of which I need to address before using the above two propositions to investigate the differences between key ideas in teaching school physics and key ideas in the discipline of physics.

In the next section, I first explain why I employ Harre's theory of *referential realism* as the epistemology. Next I explain what Harre's theory is and why Harre's theory can provide the kind of epistemology needed in this dissertation.

Why Harre's epistemology of science

Why do I use Harre's theory of referential realism as the epistemology of science, instead of constructivist epistemology which has already prevailed in the area of science education? Below I present a review of two recent critiques of constructivism--one by Phillips (1995) and another by Osborne (1996)--which provides the context for my justification of the adaptation of Harre's epistemology in this study. Following this review, I will explain what Harre's theory of *referential realism* is about. I will derive two propositions from Harre's theory which constitute another part of the conceptual framework of this study. Finally, I will explain why using Harre's theory allows me to avoid some pitfalls inherent in constructivist epistemology.

In "The Good, the Bad, and the Ugly: The Many Faces of Constructivism", Phillips (1995) provided an excellent and timely survey of the current brands of constructivism. According to Phillips, the general idea shared by all contemporary sects of constructivism can be summed up as "human knowledge--whether it be the bodies of public knowledge known as the various disciplines, or the cognitive structures of individual knowers or learners--is *constructed*":

> These days we do not believe that individuals come to the world with their "cognitive data banks" already prestocked with empirical knowledge, or with pre-embedded epistemological criteria or methodological rules. Nor do we believe that most of our knowledge is acquired, ready formed, by some sort of direct perception or absorption. Undoubtedly humans are born with *some* cognitive or epistemological equipment or potentialities.... but by and large human knowledge, and the criteria and methods we use in our inquiries, are all *constructed*. Furthermore, the bodies of knowledge available to the growing learner are themselves human constructs--physics, biology, sociology, and even philosophy are not disciplines the content of which was handed down, ready formed, from on high; scholars have labored mightily over the generations to construct the content of these fields, and no doubt "internal politics" has played some role. (p. 5)

However, a pitfall inherent in variety of constructivist epistemology is the "tendency towards relativism, or towards treating the justification of our knowledge as being entirely a matter of sociopolitical processes or consensus, or toward the jettisoning of any substantial rational justification or warrant at all" (p. 11-12). Phillips believed that "any defensible epistemology must recognize--and not just pay lip service to--the fact that nature exerts considerable constraint over our knowledge-constructing activities, and allows us to detect [or eject] our errors about it." (p. 12)

In "Beyond Constructivism," Jonathan Osborne (1996) offered a comprehensive and insightful critique of constructivism in science education. He distinguished between two positions of constructivism: the radical constructivist and the social constructivist. For the first position, Osborne argued that it inherits the tendency of blurring the relationship between scientific knowledge and natural reality:

> This position of the radical constructivist is essentially that of the instrumentalist...theories are merely portrayed as convenient devices for describing phenomena and connecting one set of events with another. They are best understood as useful fictions which bear no necessary relationship with reality and one idea is considered better than another only if it is more useful calculating and predictive device. (p. 57)

Furthermore, he argued that radical constructivist replaces the notion "truth" with the concept "viability," but fails to elaborate any criteria by which one scientific idea is judged to be more "viable" than another. He wrote,

> ....Constructivism singularly fails to elaborate any mechanism by which one theory can be consider more "viable" than another. [Von] Glasersfeld (1991) asks merely that we "try to develop a theory which offers a relatively coherent explanation" and that such theories are tested in experiential world "where they either do or do not do what they are claimed to do." The problem is that many theories, including Ptolemaic astronomy, would meet such criteria. Tobin, at least, implicitly...recognizes that some theories are more "elegant" than others but fails to elaborate any criteria by which such judgements could, or should, be made. (p. 58)

For the position of social constructivism, Osborne contended that its overemphasis on the construction of scientific knowledge through social discourse leads to the confusion between scientific knowledge and objects of scientific knowledge themselves. He explained,

> ...the "things" of science are no longer entities that populate a real world but the inventions of a scientific discourse which are "imposed on the phenomena." Hence it is not nature which limits the scientific imagination but simply human capabilities and their cultural and conceptual tools which "reflect the cumulative wisdom of the culture." Basically the confusion that occurs here is to conflate ideas and objects, that is, to fail to discriminate between the objects of the discourse with the statements of the discourse. The two are not the same, one exists and can be experienced, often with the aid of instrumentation, the other is a socially negotiated construct. (p. 61)

Taken together, Osborne concluded that constructivism is a "flawed epistemology" which is a misrepresentation of science as it is practiced, because of 1) its tendency to neglect the constraint imposed by the nature on the construction of scientific knowledge; 2) its failure "to distinguish between real and theoretical entities"; and 3)its failure "to elaborate any methodology of theory adjudication."

I sympathized greatly with both Phillips and Osborne in their assessment of constructivism. I was convinced by these two critiques as well as the critiques launched by Sokal (1996) and Weinberg (1996) that constructivist epistemology in its radical configurations[1] misrepresents certain important aspects of scientific knowledge and scientific

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[1] For example, the kinds of constructivist epistemology articulated by Von Glasersfeld (1984), Barnes (1974), Collin (1985), Longino (1993), and Harding (1993).

practice. In my search for an alternative epistemology--an epistemology that can reflect the true nature of scientific knowledge and scientific practice and that can avoid the above pitfalls inherent in constructivist epistemology--as the frame for my dissertation study, I found Harre's (1986) *referential realism*. In the following, I first present an overview of Harre's theory. I next explain why using Harre's epistemology allows me to avoid the pitfalls.

What is Harre's epistemology of science?

Harre's referential realism is a defense against the recent attacks on the trustworthiness of scientific knowledge and on the moral hegemony of scientific practice. According to Harre, there are three lines of attack. One attacks the "certainty" of scientific knowledge. Critics see that on the one hand scientific theories, practically speaking, are substantially certain, but on the other hand, scientists must be willing to revise and even to discard their theories at the moment when experimental results set against them. Another attack is launched by some sociologists of science. They argue that the life of scientists can be portrayed as "a career oriented power struggle" and that scientific research is used by scientists as "a main tool in their ruthless self-promotion and careerism" (pp. 2). The third attacks the reliability of scientific methods. Skeptics see the perennial difficulty of sustaining a claim to have a reliable scientific method for the discovery of truth and for the elimination of falsehood, with respect to a corpus of beliefs about the natural world.

In the eyes of Harre, this contemporary skepticism is absurd. If the achievements of scientists are set against those of any other facet of Western civilization, one can hardly fail to be impressed by "the vast store of knowledge that has been accumulated on almost every conceivable aspect of the natural world and by the extraordinary stability and rigid implementation of the scientific morality" (Harre, 1986, pp. 1). From his point of view, science is not only an epistemological achievement, but also a moral achievement. The scientific community exhibits "a model or ideal of rational co-operation set within a strict moral order, the whole having no parallel in any other human activity" (pp. 1). Every scientific community enforces "honesty," "trustworthiness," and "good work" as standards in their activities of scientific inquiry.

Harre perceived these attacks as a reaction to "an overblown form of realism." Many realists have based their defenses of scientific realism on "the doctrine of bivalence" (the principle that most scientific statements are true or false by virtue of the way the world is). Harre believed that such a principle "is far too strong and vulnerable to attack." In defending science from the attacks, he established a special form of realism--that is, *referential* realism--which, as he believed, is more akin to the true nature of scientific practice and that lacks the fatal feature possessed by other forms of realism. According to Harre, instead of asking "Are the statements of this theory true or false?" and doing one's best within human limitations to answer, scientists actually ask, "Do things, properties, process of this sort exist?" and do their best within human limitations to find exemplars. This position shifts the locus of the argument about realism from "truth or falsity" of statements to the question of the "existence or nonexistence" of the entities discussed by scientists.

Underlying Harre's referential realism is a basic conviction: "many of the referring expressions that occur in the theoretical discourses have referents in the world that exist independently of human cognitive and practical activity" (pp. 191). Harre argued that there are three types of entities that we experience in the world which require not a *singular* theory of science but a *triadic* one. *Type 1* theories are cognitive objects with pragmatic properties. They enable classification, explanation, and prediction of observable phenomena. An example of a typical type 1 theory is *Classical Kinematics*. Different kinds of motion can be differentiated by reference to the concepts of velocity, acceleration and so on.

Type 2 theories are cognitive objects with iconic properties. They enable the representation of certain kinds of unobservable entities which can be made available to human perceptions through experimentation. A typical type 2 theory is *Physical Optics*. The interaction of light waves is an entity which can not observed by an unaided observer, but they manifest many observable phenomena (e.g., interference and diffraction) under certain experimental conditions.

Type 3 theories are cognitive objects with mathematical properties. They enable the representation of the kind of entities which cannot be observed by human beings. Typical examples of type 3 theories include *Special Relativity* and *Quantum Field Theory*.

Corresponding with these three theory-types, there are three kinds of putative referents of substantive terms in scientific discourse, relative to the possibilities of human experience. For type 1 theories, scientists are committed to the existence of phenomena which can be available to an unaided observer. The referents of type 1 theories belong in *Realm 1*, the realm of actual objects or common-sense experience. The moon, the sun, and the Grand Canyon belong in Realm 1.

For type 2 theories, scientists are committed, not only to the ontology of Realm 1--that is, type 1 theory about actual objects or common-sense experience--but also to entities which are available to the amplified human sense through necessary technology or experiments. The referents of type 2 theories belong in *Realm 2*, the realm of possible objects of experience. Their certification as part of the real furniture of the world depends on the availability of the necessary technology or experiment. Electromagnetic waves, atoms, and electrons belong in Realm 2.

For type 3 theories, scientists are committed not only to the ontologies of Realms 1 and 2, but also to entities which could not become phenomena of human observers. The referents of type 3 theories belong in *Realm 3*, the realm of beings beyond all possible experience. Quantum states and naked singularities belong in Realm 3.

Table 2.1 - Three types of scientific theory and three realms of human experience.

Theory -types	**Realms of human experience**	**Entities**	**Functions**
Type 1	Realm 1: common-sense experience	Observable phenomena	classification, explanation, and prediction
Type 2	Realm 2: possible technologically aided, sense-experience	Unobservable mechanisms with direct empirical evidence	Representation, explanation, and prediction
Type 3	Realm 3: beyond common-sense and possible experience	Mathematical beings with no direct empirical evidence	Representation, explanation, and prediction

I use Table 2.1 to summarize three types of scientific theories and their corresponding three realms of human experience. This constitutes the third proposition of my conceptual framework.

Using Harre's epistemology in my dissertation allows me to avoid the pitfalls inherent in constructivist epistemology about scientific knowledge. What Harre's epistemology reveals to us, first of all, is that scientific discourse is not merely a human construction; scientific discourse is about a world independent of human material and cognitive practice. Realm 1, the realm of actual human experience, is indeed a part of the natural world, and not a mere representation of it. As Harre wrote, "We do touch, see physically operate with and upon things, constituents of a world that exists independently of ourselves," and "In describing things and events we perceive, we are talking *about* the things and events of a world independent of our perceptual systems." (pp. 169)

Secondly, Harre's theory clearly indicates that scientific discourse is bounded by the real would. Scientists, whether working on the frentiers (realm 3) or working in the areas of normative science (realm 2), are committed to realm 1 ontology. In a real sense, Harre's epistemology highlights the constraints imposed by the natural world in the construction of scientific knowledge, and clarifies the relationships between scientific knowledge and the natural reality, both of which are neglected or bewildered by radical and social constructivists.

Furthermore, Harre's epistemology shows that scientific discourse is grounded in material practice, rather than in propositions and statements. Since majority of scientific theories belong to type 1 or type 2, and type 1 and type 2 theories are the primary focus of this dissertation, below I examine the ways of theorizing in Realm 1 and 2 discourses to illustrate how scientific discourse is grounded material practice. The ways of theorizing in Realm 1 and Realm 2 discourses will constitute the fourth proposition of my conceptual framework.

According to Harre, theorizing in Realm 1 and 2 discourses involves the use of a "analytic analogue" and a "source analogue." A analytic analogue is a set of classificatory categories or schemes by which scientists make the world of human perceptual experience manifest patterns of various kinds of order. For the type 1 theories about *color*, for instance, "the combination of white light," "secondary colors," "primary colors," "reflection," "absorption," "transmission" constitute the analytic analogue. Through this analytic analogue, our common-sense experience about color can be differentiated into "color by reflection," "color by transmission," "color mixing by subtraction," and "color mixing by addition."

A source analogue is the theoretical model from which scientists draw concepts for representing a type 2 entity (i.e., an unobservable process or mechanism or constitution) that cause the observed patterns revealed by realm 1 discourse. Through the use of source analogues, scientists push their imagination beyond human perpetual experience in a disciplined way. The electromagnetic model and the quantum model of light can act as the source analogues for type 2 theories about color. Theoretically, by using these two models, scientists can develop representations for the interaction of light waves with the electrons and atoms in materials that cause "color by reflection," "color by transmission," "color mixing by subtraction," and "color mixing by addition."

The union of analytical analogue and source analogue in realm 1 and realm 2 theorizing reveals an ontological continuity and progression from Realm 1 (human actual experience) to Realm 2 (human possible experience). Realm 1 discourse is grounded in the physical world, and realm 2 discourse is grounded in Realm 1 discourse. Furthermore, scientific experiments play two essential roles in the development of realm 2 discourses. On the one hand, through experiments, scientists unveil some patterns in the physical world which otherwise are unavailable to or are unnoticed by our human eyes. The patterns become the base upon which scientists developed their conjectures for realm 2 entities which are responsible for the patterns. Thomas Young proposed his hypothesis that light is a wave of almost unimaginably small wavelength based upon his famous light interference experiment which demonstrated wavelike properties of light convincingly.

On the other hand, scientific experiment is the final judge for the acceptance of a type 2 theory by the community of scientists. A type 2 theory is accepted by the scientific community under the condition that some observable phenomena of the Realm 2 entities predicted by the type 2 theory itself can be discovered through scientific experiments. Maxwell's theory of electromagnetic field (i.e., Maxwell's equations) was accepted by the physicists' community only after his prediction about electromagnetic radiation was verified by Hertz in 1888. Hertz's important discovery completely bore out Maxwell's prediction and was accepted as evidence for the validity of Maxwell's equations. These two critical roles played by scientific experiments in the development of scientific discourse are captured nicely by Feynman (1995) in his "the principle of science":

> The principle of science, the definition, almost, is the following: *The test of all knowledge is experiment*. Experiment is the solo judge of scientific "truth." But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is *imagination* to create from these hints the great generalization--to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess. This imagining process is so difficult that there is a division of labor of physics: there are *theoretical* physicists who imagine, deduce, and guess at new laws, but do not experiment; and then

there are *experimental* physicists who experiment, imagine, deduce, and guess. (pp. 2)

The ways of theorizing in Realm 1 and Realm 2 discourses can be summarized in Figure 2.1. The development

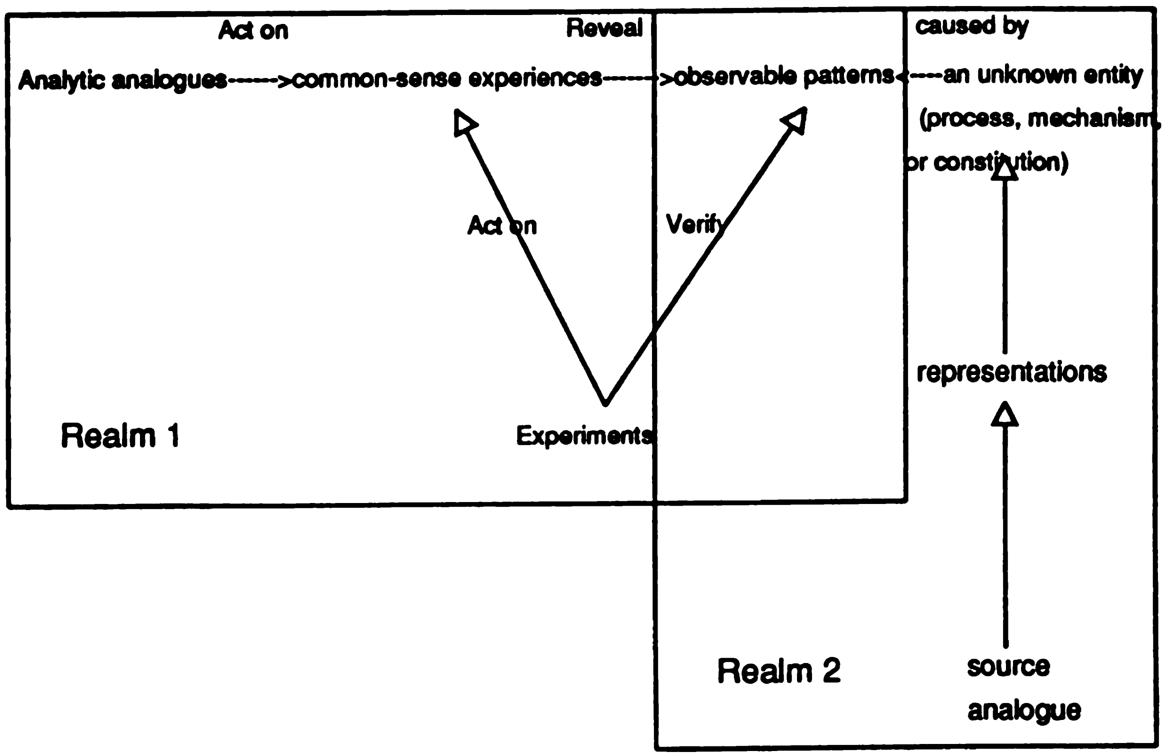

Figure 2.1 - Theorizing in Realm 1 and Realm 2 discourses

of Realm 1 and 2 discourses involves the joint use of analytic analogue and source analogue. Scientific Realm 2 discourse is grounded in the natural world and in material practice because of the ontological continuity and progression from Realm 1 to Realm 2, and because of essential roles of scientific experiments in the production and verification of scientific knowledge. Therefore, theory adjudication is not merely a "sociopolitical process." The neglect of the ontological commitment and material practice by radical and social constructivists leads to their failure to elaborate any methodology of theory adjudication in the construction of scientific knowledge.

A conceptual framework

I have derived four propositions from the above discussion of Dewey's idea of *psychologizing subject matter* and Harre's theory of *referential realism*. The conceptual framework for this study is constituted by these four propositions:

1. Given a physics topic, key ideas in the teaching of school physics represent the psychological structure of subject-matter knowledge--that is, the structure that follows the historic development of subject-matter knowledge, and that are centered around the experiences of learners. Key ideas in the intellectual discipline of physics, on the other hand, stand for the logical structure of subject-matter knowledge--that is, the structures that are characterized by a body cf finished achievements.

2. Within a cultural context, purposes of teaching, knowledge background or experience of learners, and textbooks, each in varying degree, determine what the key ideas are and how these ideas are formulated in the teaching of school physics and in the intellectual discipline of physics.

3. Key ideas in the teaching of school physics or in the intellectual discipline of physics can be categorized into three theory-types, the referents of which are relative to the possibilities of human experience. *Type 1* theories enable constitution, classification, and prediction of observable phenomena. The referent of type 1 theories belong in *Realm 1*, the realm of actual objects of human experience. *Type 2* theories enable the representation of a certain kind of unobservable entities which can only be made available to human perceptions through experimentation. The referent of type 2 theories belong in *Realm 2*, the realm of objects of possible experience. *Type 3* theories enable the representation of the kind of entities which cannot be observed. The referents of type 3 theories belong in *Realm 3*, the realm of objects beyond all possible experience.

4. The development of realm 1 discourse (or type 1 theories) involves the use of analytical analogues, and the development of realm 2 discourse (or type 2 theories) involves the use of source analogues. Realm 1 discourse is grounded in the physical world. Realm 2 discourse is developed based upon realm 1 discourse and scientific experiments.

Now I turn to justify why these four propositions constitute an appropriate and useful framework for examining and explaining the differences between key ideas in the teaching of school physics and key ideas in the intellectual discipline of physics.

First of all, the third and fourth propositions enable me to describe and interpret how key ideas in teaching school physics differ from those in the intellectual discipline of physics in a revealing and systematic fashion. We all agree that key ideas in the intellectual discipline of physics tend to be more "abstract" than key ideas in teaching school physics. What does "being more abstract" truly mean? How can we compare the "abstractness" of key ideas in teaching school physics and in the intellectual discipline of physics? The third proposition suggests that the "abstractness" can be indicated in the theory-types of the ideas and their corresponding realms of human experience. The third proposition suggests that the "abstractness" can be reflected in the analytical analogues, source analogues, empirical evidences, and scientific experiments involved in formulating the ideas.

Secondly, the second proposition, along with the first and fourth proposition, enable the explanation of why key ideas in teaching school physics differ form those in the discipline of physics. As indicated in the second proposition, purposes of teaching, knowledge background or experience, and textbooks are three determining factors in the nature of key ideas in teaching school physics and in the discipline of physics. The first and fourth propositions has important implications for each of these factors in determining what the key ideas are and how key ideas should be formulated in teaching school physics and in the discipline of physics.

Purpose of teaching. The purposes of teaching determine the theory-types of key ideas in teaching. For the purpose of making physicists or scientists, teaching in the discipline of physics would emphasize type 2 or 3 ideas (concepts or principles), because the majority of fundamental concepts or principles in the intellectual discipline of physics belongs to type 2 and 3 theories. On the other hand, for the purpose of preparing high school graduates, teaching at the high school level probably focus more on type 1 ideas (concepts or principles), because they can provide students with the important foundation for the their subsequent learning of type 2 and type 3 ideas, and because they enable students to explain and interpret the natural world.

Knowledge background of learners. The knowledge background or experience of school students is the referent for the process of restoration of key ideas in the disciplines into key ideas in teaching. It determines what the theory-types of key ideas are as well as how the key ideas are formulated. For prospective physicists and scientists who have had solid background in advanced physics and mathematics, they can straightforwardly learn type 2 and type 3 ideas, and do experiments to verify the outcomes of some type 2 ideas. However, school students are unable to learn type 2 and type 3 ideas in the fashion that prospective physicists or scientists do, due to the nature of their knowledge background or experience. Before learning certain type 2 or 3 ideas, school students need to develop their understanding of type 1 ideas--which provide a necessary grounding for their understanding type 2 or 3 ideas--through observing a wide range of macroscopic phenomena.

Textbooks. As indicated before, textbooks are the resource of key ideas in teaching school physics and in the discipline of physics. The key ideas in physics texts for prospective physicists or scientists represent the "finished" versions of scientific understandings. The majority of ideas are at type 2 or type 3 level, and are summarized in a very systematic and precise form. In this sense, these key ideas stand for the logical structure of subject-matter knowledge.

On the contrary, the majority of key ideas in a physics texts for school students are at type 1 or type 2 level. According to my preliminary analysis of the two high school texts (i.e., *Merrill physics* and *Conceptual physics*), many of the ideas in optics are more akin to the optical concepts or principles that are important in the early stages of development of scientists' understanding about light. The presentation and formulation of these ideas in the two texts reflect the logical progression in the development of scientific discourse indicated in the fourth proposition: Realm 2 discourse is developed based upon Realm 1 discourse, and Realm 1 discourse is grounded in the physical world. In this sense, the ideas in the two texts capture the kinds of experience that are critical for the derivation of key ideas in the discipline. They result from a "restoration" of the key ideas in the discipline. In this sense, key ideas in the two texts for school students stand for the psychological structure of subject-matter knowledge.

In short, these four propositions constitute a productive framework for investigating how and why key ideas in teaching school physics differ from those in the intellectual discipline of physics.

Chapter 3

DESIGN OF THE STUDY

This study was designed to investigate the nature of key ideas in teaching school physics by contrasting the key ideas in teaching three topics at the high school level with the key ideas in the discipline of physics. Two questions are central to the work: in teaching certain topics to high school students, how do the key ideas in teaching school physics differ from the key ideas in the discipline of physics? And why do the key ideas in teaching school physics differ from the key ideas in the discipline of physics.

The work was composed of a case study of two high school experienced physics teachers, a contrast of the key ideas in teaching the three topics at the high school level with the corresponding key ideas in teaching the topics for prospective physicists or scientists, and interviews with the two physics teachers and two professors who are specialized in the topics.

1. The case study of two high school experienced physics teachers. The main purpose of the case study was to reveal what the key ideas are, and how the key ideas are formulated in teaching certain physics topics at the high school level. I assumed that in teaching a particular physics topic at the high school level, an experienced physics teacher usually is more capable of focusing his or her instruction on a limited set of key ideas than a novice

a teacher is.[1] An experienced physics teacher has a sound understanding of what key ideas are and why the ideas are important in teaching the topic based upon his/her teaching experience which Shulman (1987) called *practical wisdom*. These two assumptions were the main reasons why I decided to study experienced physics teachers.

The two high school teachers. The two teachers I studied, Mr. Kennedy and Mr. Barnes (pseudonyms), had taught high school physics for more than thirty years. They both had a strong subject-matter background in physics. Mr. Kennedy holds a B.S. in electrical engineering and a M.S. in physics. Mr. Barnes has a B.S. in chemistry with a minor in physics. He took graduate course works in advanced physics while working on a M.A. in educational administration. The excellence of their teaching was well recognized by their school districts. Both of them were selected as the mentors for novice physics teachers by a large university in midwest. Mr. Kennedy was honored as the "master teacher" in physics by the school district. Mr. Barnes had been one of the finalists for the honorable title "The Most Distinguished Physics Teacher in the State."

Data collection and preliminary data analysis. My observation of the two teachers' teaching was divided into two periods. From the beginning of February through the

[1]This assumption finds empirical confirmation from some case studies of mathematics teachers (e.g., Leinhardt, 1988; Leinhardt & Smith, 1985; Lampert, 1986).

middle of April 1996, I observed Mr. Barnes' teaching about mechanical waves, sound waves, and light waves. From the middle of April through the early of June 1996, I observed Mr. Kennedy's teaching of the same sequence. In each of my visits to their classrooms, I took field-notes, collected a copy of teacher handouts, and chatted with the teacher occasionally. I also obtained a copy of the textbooks (i.e., *Merrill Physics* and *Conceptual Physics*) used by the two teachers.

While data collection was going on, I was also doing preliminary data analysis of what the key ideas were and how the key ideas were formulated in teaching some topics in the chapter on "light" to high school students, through examining the textbooks and writing expanded versions of field-notes and analytic memos (see Miles & Huberman, 1994). I was also comparing some of the ideas in teaching the chapter on "light" with their parallel ideas in two *Optics* texts for prospective physicists or scientists (i.e., Hecht & Zajac, 1979; Klein & Furtak, 1986). The preliminary analysis eventually led me to focus the study on three topics: *color*, *the speed of light*, and *light interference*.

I decided to study the topic *color* because of my interest in testing the hypothesis that *color* was an important topic in teaching optics for high school students, and yet was negligible in teaching optics for prospective physicists or scientists. I raised this hypothesis from my personal experience in learning to teach *color* as a beginning physics teacher in China. I was unable to teach it even though I had one year of course work on *Optics* at the college level. Examining the topic *color*, I believed, could reveal a mismatch between what high school physics teachers need to teach and what they learn from the academic discipline of physics, and could deepen the understanding about the nature of key ideas in teaching high school physics.

My decision to study the topic *the speed of light* was due to the surprise I had while watching the teaching of this topic by the two experienced physics teachers. I was amazed at the examples, analogies, and questions provided by the two teachers in helping students make sense of "how fast light can travel." However, in the academic discipline of physics, *the speed of light* is normally taken as a given physical constant. It occurred to me that holding a bachelor's degree in physics doesn't guarantee that physics teachers will able to truly convey "how fast light can travel" to high school students through examples, analogies, and questions. Investigating this topic, I believed, could contribute to my understanding about the kind of translation from a key idea in the discipline to the key idea in teaching school physics.

I was interested in examining the topic *light interference* because of the sequence which teaching high school optics follows normally. Instead of using the electromagnetic model of light as the starting point, the teaching of high school optics starts with teaching "water waves interference," "sound waves interference," and eventually moves toward teaching "light interference." Exploring this topic, I believed, would allow me to understand better how and why the formulation of key ideas in teaching school physics differed from their formulation in the intellectual discipline.

Analyzing key ideas in teaching. An in-depth analysis of the key ideas in teaching the three topics was conducted after completion of data collection. I first analyzed the two high school texts to determine what the key ideas were, and how these key ideas were formulated for each of the three topics at the high school level. As already indicated in chapter two, a high school text can be an important resource for a high school physics teacher to determine what the key idea are, and how the key ideas should be formulated in teaching a particular topic to high school students. At the end of each chapter each of the two high school texts, *Merrill Physics* and *Conceptual Physics,* provides a chapter review section. The ideas and concepts important in teaching a particular topic are summarized through a set of propositional statements, which provide good indicators about the key ideas and their related concepts or terms for each topic. To examine how these key ideas are formulated, I read each text over and over again with several specific questions in mind: what are the theory-types of each of the statements? What are the analytical analogues or source analogues in formulating each idea? What is the empirical evidence involved in the establishment of each idea? I also analyzed the teaching objectives developed by each teacher. Teaching objectives could also be good indicators because they summarize what teachers want students to know.

I next analyzed the lessons on each of the three topics taught by each teacher to determine what the key ideas were and how these key ideas were formulated to high school students. The unit of analysis for an individual lesson was an instructional event or a series of instructional events which was pertinent to teaching one specific idea. For each event or a series of events, I constructed a vignette to capture the idea the teacher sought to teach, the sort of phenomena or mechanism that the idea explains, the analytical analogue or source analogue, and empirical evidence involved in formulating the idea. A set of vignettes--each of which elucidated the teaching of one idea within an individual lesson--could unveil what ideas each teacher emphasized, how one idea was related to other ideas or concepts, and how the ideas were conveyed to students.

For each case, I drew and verified the conclusions about what the key ideas were and how the key idea were formulated by triangulating various sources of evidence: the textbook, the lessons, the teacher's handouts (e.g., the objective sheets), and the teacher interviews (I discuss the interviews with the two teachers in 3 below).

2. A contrast of the key ideas in teaching the three topic for high school students with the key ideas in the discipline of physics. The question this comparison sought to answer was, how do the key ideas in teaching the three topics at the high school level differ from the key ideas in the discipline? To uncover what the key ideas are and how these key ideas are formulated in the discipline, I first examined two optics textbooks which were written exclusively for prospective physicists or scientists: Hecht & Zajac's (1979) *Optics* and Klein & Furtak's (1986) *Optics*. I next interviewed two optics professors to substantiate and refine my understanding about the key ideas for the three topics developed through my examination of the two texts (see 3 below for the interviews).

Hecht & Zajac's *Optics* was recommended by the two optics professors whom I interviewed. They both regarded it as a "sound text" and used it as the only required text in their optics courses. I selected Klein & Furtak's *Optics* because it was written not only as a text, but also as a "general reference on the fundamentals of optics." As already indicated in Chapter two, the ideas essential for physicists or scientists to know for a particular branch of physics are illustrated and summarized in a limited number of up-to-date textbooks. Given the fact that optics is one of most ancient and the well-established areas in the disciplines of physics, I believe an examination of these two optics texts, following by verification and refinement by two optics professors, can yield valid and reliable information of what the key ideas are and how the key ideas are formulated for the three topics in the area of optics within the intellectual discipline of physics.

For the key ideas in teaching the three topics at the high school level, I first differentiated between type 1 and type 2 key ideas according to the two different realms of human experience (Realm 1 and Realm 2) in which each idea belongs. The differentiation led to four possible kinds of comparison: 1) type 1 ideas at the high school level versus type 1 ideas in the discipline; 2) type 1 ideas at the high school level versus type 2 ideas in the discipline; 3) type 2 ideas at the high school level versus type 1 ideas in the discipline; and 4) type 2 ideas at the high school level versus type 2 ideas in the discipline.

For the first comparison, I contrasted the analytic analogue used in teaching high school physics with the analytic analogue used in the discipline. For the second & third comparisons, I contrasted the macroscopic phenomena (which type 1 ideas classify) with the unobservable entity responsible for the macroscopic phenomena (which type 2 ideas seek to represent), and the role of type 1 ideas with the role of type 2 ideas in developing our understanding about the nature of the phenomena. For the last comparison, I contrasted the source analogue and empirical evidence used in teaching high school physics with the source analogue and empirical evidence in the discipline. Table 3.1 summarizes these two contrasts.

Table 3.1 - Four possible kinds of comparison between key ideas in teaching and key ideas in the discipline

High school\Discipline	Type 1	Type 2
Type 1	Analytic analogue vs. analytic analogue	Observable phenomena vs. unobservable entities Manifesting patterns vs. representing mechanisms that cause the patterns
Type 2	Observable phenomena vs. unobservable entities Manifesting patterns vs. representing mechanisms that cause the patterns	Source analogue vs. source analogue Empirical evidence vs. empirical evidence

<u>3. Interviews with the two physics teachers and two optics professors</u>. The main purposes of the interviews with the two teachers were 1) to understand what the key ideas are and how they are formulated in teaching *color, the speed of light*, and *light interference* at the high school level, and 2) to understand why the key ideas in teaching each of the three topics at the high school level differ from those

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in the discipline from the perspectives of the two teachers.

Each physics teacher was interviewed twice. These two tape-recorded interviews were structured and opened-ended. Each took about forty minutes. The first interview was designed to collect data on each teacher's beliefs about the importance of *color* and *the speed of light* at the high school level, beliefs about how the key ideas in teaching these two topics differed from the key ideas in the discipline, beliefs about purposes of teaching (goals and objectives), beliefs about knowledge background or experience of the students, and beliefs about teaching and learning physics. The second interview was designed to collect data on each teacher's definition of key ideas; criteria for including or excluding key ideas; criteria for selecting hands-on experiments, demonstrations, and video-tapes for teaching; and beliefs about the key ideas in teaching the topic *light interference*. In addition, it was used as a follow-up interview to elicit each teacher's responses to some questions which I generated based upon my analysis of the first interview (for the interview protocols, see appendix A).

The main purposes of the interviews with the two optics professors were 1) to understand what the key ideas are and how the key ideas are formulated in relation to the three topics in the discipline, and 2) to understand how and why the key ideas in the discipline differ from the key ideas in teaching the three topics at the high school level from the perspectives of the two optics professors.

For one professor, I conducted two structured, opened-ended, and tape-recorded interviews, each of which took about forty minutes. The first interview was designed to collect data on the professor's beliefs about the purposes of teaching, his assumptions about knowledge background or experience of prospective physicists or scientists, the texts used in his optics course, and his assumptions about the key ideas about *color, the speed of light*, and *light interference* in the discipline. The second interview was designed to elicit his responses to the central issues: how and why the key ideas in the discipline differ from those in teaching the three topics at the high school level (for the interview protocols, see appendix B). For the second optics professor, I conducted a one and a half hour tape-recorded interview which combined the above two interviews into one.[2]

Throughout the process of analyzing the interview data, I relied on conceptual memos as an analytical technique. A memo can be defined as "the theorizing writing-up of ideas about codes and their relationships as they strike the analyst while coding....it can be a sentence, a paragraph or

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[2]The decision of combining two interviews to one was based on two considerations: the stage of maturity in the study and the inconvenience in meeting professor B. By the time I interviewed professor B, I had completed most data analysis. Professor B was a faculty in a university 80 miles away from the MSU campus.

a few pages...it exhausts the analyst's momentary ideation based on data with perhaps a little conceptual elaboration" (Glaser, 1978, p. 83-84; in Mike & Huberman, 1994). Miles & Huberman (1994) believed that "Memos are primarily conceptual in intent. They don't just report data; they tie together different pieces of data into a recognizable cluster, often to show those data are instances of a good concept" (p. 72). The first stage of interview data analysis involved careful transcribing and analyzing each interview tape. While transcribing an interview tape, I made notes of all hypotheses, ideas, surprises, or questions which I had in relation to my research questions, the conceptual framework, as well as what I saw in the classrooms. Writing these memos enabled me to generate propositions, or connected sets of statements, reflecting the findings of this study.

The second stage of analysis involved cross-case analysis. For each of the interview questions, I looked at the transcripts for themes common to the two high school teachers and then summarized these themes in a conceptual memo. For instance, helping high school students explain and interpret the natural world was one of their common purposes of teaching, and it was also their main justification for the importance of teaching *color* at the high school level. Writing a memo enabled me to unveil and clarify the relationship between why a teacher taught physics and what

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the teacher thought was important in light of teaching *color* at the high school level.

I followed the same procedure while analyzing the transcripts of the two optics professors' interviews. I noticed that elucidating the characteristics of type 2 optical concepts--which are quantitative and abstract, but in fact have empirical consequences--was the common purpose shared by the two professors. I also noticed, from the responses of the two professors, that *color* was not taught for prospective physicists or scientists due to the non-sophisticated and descriptive feature of type 1 ideas about *color*. Writing a memo enabled me to reveal the link between why a professor taught optics and what ideas he considered important.

The third stage of analysis contrasted the responses provided by the two teachers and the responses provided by the two professors. The purpose of the contrast was to develop explanations about why the key ideas in teaching *color*, *the speed of light*, and *light interference* at the high school level differed from those in the discipline in light of the differences in assumptions about purposes of teaching and about knowledge background or experience of learners between the two teachers and the two professors. Again, I wrote a conceptual memo to summarize each contrast.

Finally, I need to point out that the essence of this study is an analytic generalization, in which "a previous developed theory is used as a template with which to compare the empirical results of the case study" (Yin, 1989, p. 38). Although the study only examined the key ideas about three topics taught by two teachers, its research findings could be generalized to some theoretical propositions about the nature of key ideas in teaching school physics. As Yin (1989) suggested, "Case studies...are generalizable to theoretical propositions and not (emphasis added) populations or universe...and the investigator's goal is to expand and generalize theories" (p. 38). This dissertation investigated the nature of key ideas in physics teaching within a theoretical context (Dewey's idea about *psychologizing subject matter* and Harre's theory of *referential realism*) and an empirical context (research on science teachers' pedagogical content knowledge and content knowledge). It thus created the potential of making contributions to our conceptualization of subject matter knowledge in science teaching and of science teachers' subject-matter knowledge.

Chapter 4

THE KEY IDEAS IN TEACHING *COLOR, THE SPEED OF LIGHT*, AND *LIGHT INTERFERENCE* AT THE HIGH SCHOOL LEVEL

Chapter four presents my analysis of the two cases of high school physics teaching: Mr. Kennedy and Mr. Barnes. The questions I seek to address are, **what are the key ideas in teaching *color, the speed of light,* and *light interference* at the high school level? And how are these key ideas formulated?** Proposition 3 & 4 (see chapter 2)--which are about different theory-types of ideas and ways of theorizing-- from my conceptual framework provide primary theoretical perspectives for this analysis.

For each case, the analysis is composed of three parts. The first part is my analysis of the textbook used by each teacher--that is,*Conceptual Physics* by Mr. Kennedy or *Merrill Physics* by Mr. Barnes. For each topic, I first lay out the key ideas summarized in the chapter review section. Next I elucidate the theory-type, the analytical analogue or source analogue, and empirical evidence for each of the ideas. Finally, I construct a semantic map to display the formulation of the key ideas.

The second part is my analysis of classroom teaching by each teacher. For each topic, I construct a series of vignettes, each of which focuses on the teaching of one key idea. Through this set of vignettes, I elicit the theory-type, the analytical or source analogue, and empirical evidence for each of the key ideas. I finally develop a semantic map to summarize the formulation of the key ideas.

The last part of analysis involves drawing/verifying conclusions about what the key ideas are and how the key ideas are formulated in teaching each of the three topics to high school students. I triangulate various sources of evidence: the text, classroom teaching, the teacher's handouts, and the teacher's interviews.

PART ONE: *COLOR*

The Case of Mr. Kennedy

I. <u>The Key ideas about *color* in *Conceptual Physics*</u>

In the text *Conceptual Physics*, the key ideas about *color* are labeled as 1) "the combination of white light," 2) "color by reflection and by transmission," 3) "color mixing by addition;" and 4) "color mixing by subtraction." [1]

<u>1. The combination of white light</u>. This idea is stated as "white light is a combination of light of all visible frequencies" (pp. 416). It is illustrated through a recapitulation of the famous Newton's investigation of color:

> Isaac Newton was the first to make a systematic study of color. By passing sunlight through a triangular-shaped glass prism, he was first to show that sun light is composed of a mixture of all the colors of rainbow....Sunlight is an

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[1] *Color* is a big chapter in *Conceptual physics*. In addition to the basic ideas about the formation of color. *Conceptual Physics* discusses "why the sky is blue," "why water is greenish blue," and "the atomic color code--atomic spectra" which are not the focus of this dissertation.

> example of what is called **white light**....Newton showed that the colors in the spectrum were a property not of the prism but of white light itself. He demonstrated this when he recombined the colors with a second prism to produce white light again... In other words, all the colors, one atop the other, combine to produce white light. Strictly speaking, white is not a color but a combination of all the colors (pp. 339).

This idea is very important in the formulation of other three ideas about *color*.

2. Color by reflection and by transmission. This idea can be summarized as "the color of an object is due to the color of the light it reflects or transmits. Light is absorbed when its frequency matches the natural vibration frequencies of the electrons in the atoms of a material illuminated by the light" (pp. 416). It is portrayed at both the type 1 and type 2 levels.

At the type 2 level, *Conceptual Physics* first introduces "the interaction of sound waves with tuning forks" as the source analogue:

> The colors of most objects around you are due to the way the objects reflect light. Light is reflected from objects in a manner similar to the way sound is "reflected" from a tuning fork when another that is nearby set it into vibration. A tuning fork can be made to vibrate even when the frequencies are not matched, although at significantly reduced amplitudes....(pp. 400)

It develops representations for the Realm 2 entity--the interaction of light with atoms and electrons--that causes reflection, absorption, and transmission as follows:

> The same is true of atoms and molecules. We can think of atoms and molecules as three-dimensional

> tuning forks with electrons that behave as tiny oscillators that can vibrate as if attached by invisible springs....Electromagnetic waves (such as light). Like acoustical tuning forks, once vibrating, they send out their own energy waves in all directions. (pp. 401)

The text thus formulates the type 2 ideas of reflection, absorption, and transmission:

> Different kinds of atoms and molecules have different natural vibration frequencies. The electrons of one kind of atom can be set into vibration over a range of frequencies different from the range of other kinds of atoms. At the resonant frequencies where the amplitudes of oscillation are large, light is absorbed. But at frequencies below and above the resonant frequencies, light is re-emitted. If the material is transparent, the re-emitted light passes through it. If the material is opaque, the light passes back into the medium from which it came. This is reflection (pp. 401)

At the type 1 level, the text uses "the combination of white light," "reflection," "absorption," and "transmission" as the analytic analogue to formulate two type 1 ideas--"color by reflection" and "color by transmission"--that can explain a wide range of common-sense experiences about color:

> "Color by reflection"
> Most materials absorb some frequencies and reflect the rest. If a material absorbs most visible frequencies and reflects red, for example, the material appeared red. If it reflects all the visible frequencies, like the white part of this page, it will be the same color as the light shines on it. If a material absorbs all the light that shines on it, it reflects none and is black.
>
> "Color by transmission"
> The color of a transparent object depends on the color of the light it transmits. A red piece of glass appears red because it absorbs all the colors that compose white light, except red, which

> it transmits, Similarly, a blue piece of glass appears blue because it transmits primarily blue and absorbs the other colors that illuminate it. (pp. 402-403)

3. Color mixing by addition. It is about "the mixing light of different frequencies [or colors]" (pp. 416). This is a type 1 idea because mixing colored lights belongs in the realm of observable phenomena. "The combination of white light," "primary colors," and "secondary colors" constitute the analytical analogue for formulating this idea.

Conceptual Physics first draws on the idea, "the combination of white light," to illustrate "primary colors" (red, green, and blue) and "secondary colors" (magenta, yellow, and cyan):

> All the visible frequencies mixed together produce white. Interestingly enough, white also results from, the combination of only red, green, and blue light... When a combination of only red, green, and blue light of equal brightness is overlapped on a screen, it appears white. Where red and green light alone overlap, the screen appears yellow. Red and blue light alone produce the bluish-red color called *magenta*. Green and blue light alone produce the greenish-blue color called cyan. (pp. 404)

Then the text suggests that any color can be a combination of primary colors or secondary colors:

> In fact, almost any color at all can be made by overlapping light of three colors and adjusting the brightness if each color of light. The three colors do not have to be red, green, and blue, although those three produce the highest number of different colors. This amazing phenomenon is due to the way of the human eye works. (pp. 405)

4. Color mixing by subtraction. "color mixing by subtraction" is about "the mixing of colored paints or dyes,

which absorb most frequencies [colors] except for the ones that give them their characteristic color" (pp. 416). It is also a type 1 idea because mixing colored paints or dyes belongs in the realm of common-sense experiences. "Reflection," absorption," "secondary colors," and primary colors" form the analytical analogue for this idea.

The text first illustrates the idea of color mixing by subtraction through "reflection," "absorption," and "the combination of while light":

> Blue paint, for example, reflects mostly blue light, but also violet and green; it absorbs red, orange, and yellow light. Yellow paint reflects mostly yellow light, but also red, orange, and green; it absorbs blue and violet light. When blue and yellow paints are mixed, then between them they absorb all the colors...except green. The only color they both reflect is green which is why the mixture looks green. This process is called *color mixing by subtraction* [Italic original]....(pp. 407)

The text suggests that "color mixing by subtraction" obeys the rules of color subtraction--"secondary colors" (magenta, yellow, and cyan) and "primary colors" (red, green blue):

> You may have learned as a child that you could make any color with crayons or prints of three so-called primary colors: red, yellow, and blue. Actually, the three paint or dye colors that are most useful in color mixing by subtraction are magenta (bluish red), yellow, and cyan (greenish blue). These are the colors used in printing illustrations in full color. (pp. 408)

At the type 1 level, the formulation of "color by refection," "color by transmission," color mixing by subtraction," and "color mixing by addition" can be laid out schematically as in Figure 4.1. These four idea capture

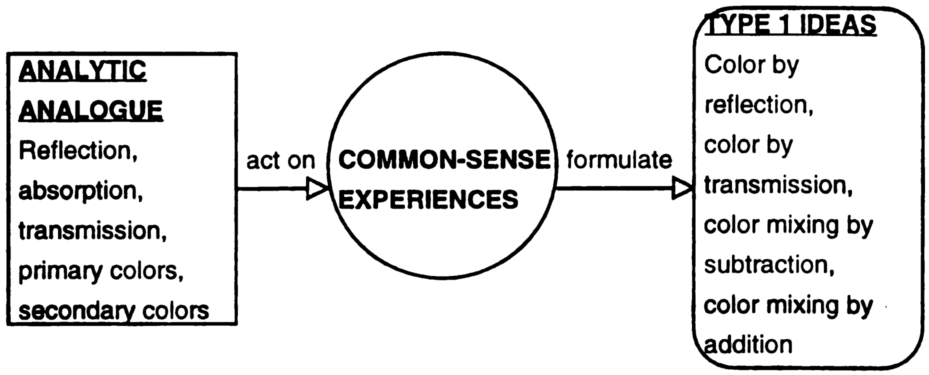

Figure 4.1 - The formulation of type 1 ideas about color in *Conceptual Physics*

four distinctive patterns of color formation which are embedded in our common-sense experiences. "The combination of white light," "reflection," "transmission," "absorption," "primary colors," and "secondary colors" constitute the analytic analogue in formulating these four ideas.

II. The teaching of *color* by Mr. Kennedy

The teaching of *color* by Mr. Kennedy I concentrated on examining consisted of two lessons. The ideas he covered in the two lessons included 1)"the combination of white light," 2)"color by reflection," 3)"color mixing by subtraction," 4)"secondary colors, primary colors, complementary colors," and 5) "color mixing by addition."

1) "The combination of white light"

The teaching of "the combination of white light" involved a quick review of the idea, and the use of a "ROY G BIV" diagram and a "rainbow" demonstration.

Mr. Kennedy started with the lesson with a bit of excitement. "We are going to the wonderful world of color," and he said again, "We are entering into the wonderful world of colors, isn't that great?" He went through the first idea quickly. "There is no white light because white light actually contains all the colors." And he added, "Before the day of Isaac Newton, it was real hard for people to believe that white light contains different colors, and yet it was not surprising today that even students at middle school knew about this fact."

On the board, Mr. Kennedy wrote a series of letters "ROY G BIV" to represent seven colors, and he drew a arrow under this series of letters to represent the increase of their frequencies (see Figure 4.2).

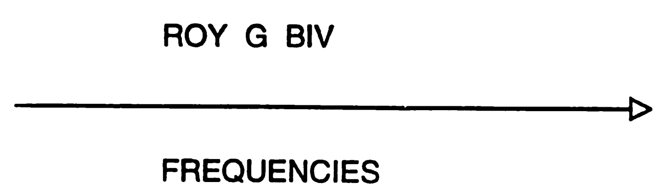

Figure 4.2 - The increase of frequency of seven colors

He picked up the color model. It looked like a small pyramid made up by a chain of donuts with different colors and sizes, piling up from red to violet, from large to small. He suggested that students should play with it after class, and told them that the model could help them memorize the relationship because the physical size of each "donut" could represent the frequency of each color of light.

"Does anybody know about seven colors, seven lucky number?" "How many of you have seen a rainbow on a crystal or window?" asked Mr. Kennedy. He moved to a lab table in the back of students and turned on a projector which was already set up. Immediately, a very beautiful "rainbow" (a spectrum of colors), was displayed on the large screen in front of the students. He told them that white light was dispersed to form the rainbow.

2)"Color by reflection"

In teaching "color by reflection," Mr. Kennedy explained nine questions related to our common-sense experiences about color in the student packets.[2] Many of these explanations were tied up with demonstrations in the classroom. "The combination of white light," "reflection," and "absorption" are the important concepts or terms used in

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[2]The study packet contained objectives, study notes, questions, and description of experiments for each unit. Developed before word processing, the pages in the packet was typed by a manual typewriter. Mr. Kennedy rarely refereed students to the objectives and study notes in the packet. What he had been using in teaching were some of the questions and experiments. For these reasons, I didn't include the packet in my analysis of the textbook.

the explanations.

The first question was, "What is the difference between an object that appears red and one that appears blue?" Standing behind the podium, Mr. Kennedy placed two pigments--one was red and the other was blue--on his chest. He asked, "What colors are falling out?" After letting students think for a moment, he explained that red pigment only reflected red and absorbed all colors except red, and the blue pigment reflected blue and absorbed all colors except blue. He asked further, "What color is resonated?" He explained, "As white light came into the red pigment, electrons were forced into vibration, energy got so high that some resonances were formed and the light of all non-red colors was absorbed...."

Mr. Kennedy rephrased the second question--"Why do the colors of various objects appear different when illuminated by different light sources?"--as "If we shine green light on red apple, what do you see?" and "What is the nature of light source illuminate?" He paused for a moment, and then explained, "No red, nothing to reflect...what get reflected? Nothing! It looks black!" He added, "By the same token, if red shines on green, it looks black because there is nothing to reflect."

The third question was, "It is now a familiar observation that the color of cloth may appear different when viewed in artificial light (fluorescent and incandescent bulbs) and in sunlight. Explain why." To explain it, Mr. Kennedy hung a large cardboard on the top of the board. On the cardboard there were many small pigments with different colors. Through the projector, he first shined red light on the cardboard. "What color appears dark?" asked Mr. Kennedy. "Green," some students answered. He asked further, "Why is it dark?", and he explained, "Only red light comes in, not green to reflect, it looks dark!" Mr. Kennedy then put a blue filter on the light source. He told students, "Put a blue filter on it, it looks like a blue world." And then he said, "See all the darkness on the cardboard....So we have a variety of colors."

Mr. Kennedy went through the fourth, fifth, and sixth questions quickly. Question 4: "Think of the color of leaves in spring or summer. What range of colors do you think that the light involved in photosynthesis has? Explain." He first asked, "What color of light is reflected?" "Green," some students responded. He pointed out that green was not being absorbed and all non-green colors were absorbed. In discussing the fifth question, "Given a red rose with a green stem, how would it appear when illuminate with the following lights ? a) white b) red c) green d) blue", Mr. Kennedy helped students come up with the answers and wrote down on the board as follows:

White	----	Normal
Red	----	Red
Green	----	Black and green
Blue	----	Dark

For the sixth question--"Red light falls upon a red rose with a green stem. Does the temperature of the rose or the stem increase more? Why? How about illumination with green light?"--he simply reminded students that light carried energy when it was absorbed.

The seventh question had two small questions: "a) What color clothing is "coldest" on hot days? Explain why. What color is "warmest"? Why?; b) Why is the sunlit surface of a black car so much hotter than the sunlit surface of a white car?" After reminding students that white reflects all colors and black absorbs all color, Mr. Kennedy said, "Give me some examples in your daily living." One student mentioned that her dog with different colors under sunshine, and she felt the black part warmer and the white part cooler. Another student said that in Arizona the most popular color of a car is white because white reflects all sun light.

The eight question was, "What color would a red car appear to be if it were under a lamp that emitted only blue light in dealer's showroom at night." "What color?" asked Mr. Kennedy. "Black," some students answered. He immediately moved to the second question: "A performer wears blue clothes. How could you use spot-lights to make them appear black?" Many students in the class seemed to come up the answer, "black or yellow," easily.

The last question involved a story situation:

> Just before the Battle of Midway in World War II, the U.S. submarine Trigger ran through on a reef.

> The officers were wearing red goggles [in order to dark adapt]. On their maps, the reefs were marked in red. Why did they run aground?"

Mr. Kennedy first passed a small piece of red transparency to each student, and he asked each student to close one of his or her eyes and then look through the red transparency. He hung a piece of cardboard on the board. On the cardboard, there were several characters "PHYSICS" with red color. "What can you see?" Asked Mr. Kennedy. "Nothing! Now you can appreciate how they had missed."

3) "Color mixing by subtraction"

The teaching of "color mixing by subtraction" involved two diagrams and a demonstration. "The combination of white light," "reflection," and "absorption," again, are the concepts used in the explanations of the idea.

"Let me give you some surprising." As he said, he drew two diagrams on the board (see Figure 4.3). One represented

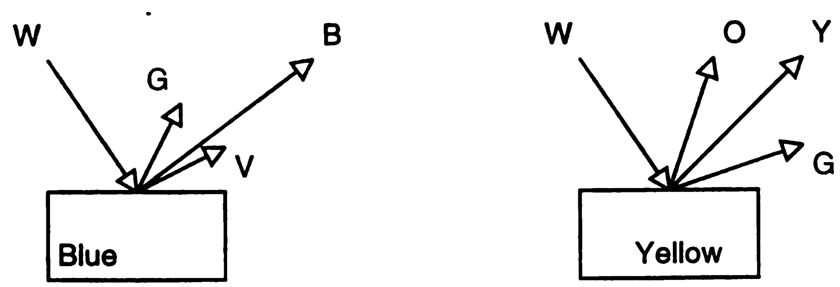

Figure 4.3 - Projections of white light on blue and yellow pigments

the projection of white light on a blue pigment and its reflection, and the other represented the projection of white light on yellow pigment and its reflection. He told students that in the reflection from the blue pigment, there were green, blue and violet, and in the reflection from the yellow pigment, there were green, yellow, and orange. He asked, "What is the only color naturally reflected green?"

He put a piece of yellow transparency and a piece of blue transparency on the overhead in front of all students, and let them overlap partially. The color of the overlapping area soon became green. He told students that yellow and blue have something in common. Then he did the same with other two small pieces of transparency--one was red and the other was green. This time the overlapping area became dark. He explained that red and green have nothing in common.

<u>4)"Secondary colors, primary colors, and complementary colors"</u>

The ideas of secondary colors, primary colors, and complementary colors are essential in the following explanation of "color mixing by addition." The teaching involved defining terms, demonstrations, and explaining some questions in student packets.

Mr. Kennedy wrote on the board that primary colors include "red," "yellow," and "blue," and secondary colors include "magenta," "yellow," and cyan." He told students that "with proper proportion of the three secondary colors, you could duplicate all kinds of color."

"Let me do a demonstration," he said, he turned on the overhead projector in front of the class, and placed a yellow transparency on it. "Let's start with yellow. You don't know what the picture is." What I could see were some yellow spots spreading over the screen. "I stamp a magenta on top, now you can see what picture is." After he placed a magenta transparency on the top of the yellow one, a figure of a basket with bananas, apples and grape inside, appeared on the screen. "Now I stamp another one, cyan." As he placed a cyan transparency on the top, immediately, a basket of bananas, apples and grape with impressive colors emerged from the screen.

Following the demonstration, he had students look at a question in their packets. The question actually consisted of a set of sub-questions:

a) What are the three secondary colors?
b) What are the three primary colors?
c) What are complementary colors?
d) What is the complement of red? Magenta? Yellow?

He first defined three secondary colors (magenta, yellow, and cyan) and the three primary colors (red, green, and blue). Then he drew a triangle on the board, with "red," "blue" and "green" at the three angeles and "cyan," "magenta" and "yellow" on the three sides, to represent their complementary relationships (see Figure 4.4).

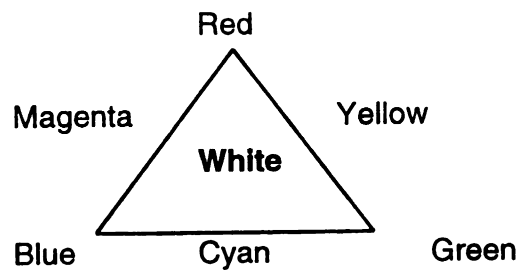

Figure 4.4 - A color triangle:

For question c) and d), he helped students come up with each pair of complementary colors through pointing them to the triangle. And he wrote down the answers on the board: for question c),

Red	-------	Cyan
Green	-------	Magenta
Blue	-------	Yellow

For question d),

Cyan	-------	Red
Magenta	-------	Green
Yellow	-------	Blue

<u>5)"Color mixing by addition"</u>

He began with a brief clarification of the distinction between "color mixing by subtraction" and "color mixing by addition." Mr. Kennedy explained, "When we talk about color substraction, we are talking about adding pigment of light; and when we talk about color addition, we are talking about adding colored lights."

The second set of questions Mr. Kennedy had students look at in their packets was directly related to "color addition":

a) Green light + magenta light = _____light.
b) Red light + green light = ______light.
c) Red light + blue light = ______light
d) White light - blue light = _____light
e) White light - cyan light = _____light

"Let's go back to what we did on Friday. Magenta is combination of what?" Asked Mr. Kennedy. He told students that magenta is the combination of red and blue, and that cyan is the combination of green and blue. Following that, he turned on two projectors which had already been set up on a lab table behind all students. By using different colored light sources, he demonstrated "green + magenta = white," " red + green = yellow," "blue + red = magenta," "green + blue = cyan" and "yellow + blue = white" to students.

The last question involved a real situation:

> Stare at piece of colored paper for a minute or so. The cones in the retina receptive to the color of the paper become fatigued, so that when you look at a white area you seen afterimage of the complementary color. This is because the fatigued cones send a weaker signal to the brain. All the colors produce white--but all the colors minus one produce the complementary color. Try it and see.

Mr. Kennedy hung a American flag on the backboard. He asked students to stare at one of the red strips for one minute, and he counted the time. After one minute, he asked students to close their eyes for a while and then opened them to look at a while area. I followed all his instructions closely. As I opened my eyes to look at the wall, I saw an image of a American flag with all cyan strips.

After the experiment, Mr. Kennedy shared with students his experience watching football games with his wife. In one game, he concentrated all his attention on what was going on in the green field for a long period of time. He closed his eyes and then open them to look at the sky. He said: "Hi, honey! I saw a magenta sky!...."

Schematically, the formulation of "color by reflection" "color mixing by subtraction," and "color mixing by addition" can be laid out as in Figure 4.5. They are type 1 ideas because they can explain a range of common-sense experiences about color created by questions and demonstrations. "Reflection," "absorption," and "the combination of white light," "primary colors, secondary colors, and complementary colors" are the analytic analogue for these three ideas.

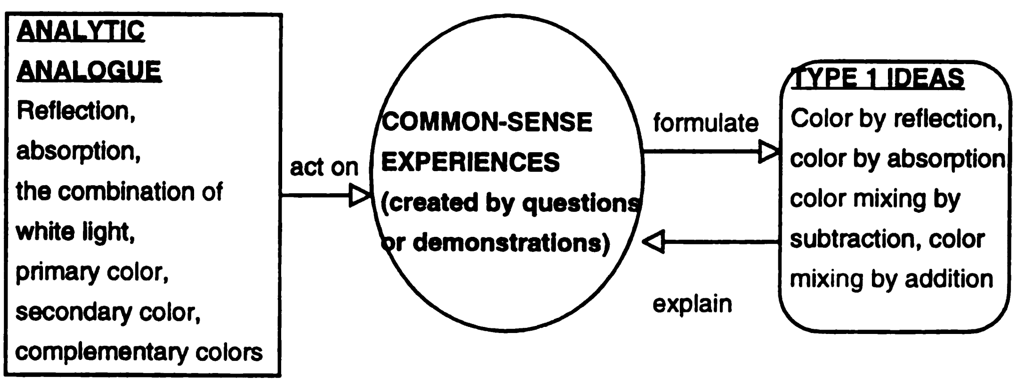

Figure 4.5 - The formulation of type 1 ideas about *color* by Mr. Kennedy

III. **Key ideas about *color*: Interviews with Mr. Kennedy**

As revealed from the above analysis of the two lessons, "the combination of white light," "color by reflection," "color mixing by subtraction," and "color mixing by addition" were the key ideas in the teaching of *color* by Mr. Kennedy. These were also evident in Mr. Kennedy's comment on what key ideas about *color* were before teaching the topic during an interview. As he stated,

> Key ideas about color? Okay, different colors correspond to different frequencies, and correspond different wavelengths. And then we are going into color by reflection and color subtraction. Why do certain objects look the color they do?....And then something they haven't been exposed to before, for that reason it is kind of difficult, they don't have the experience but they certainly like it. It is color addition....So I think it's important that we touch color. See we only spend a day on color subtraction and a day on color addition....(IT-Kennedy, 5/28/96)

As compared to the key ideas in *Conceptual Physics*, Mr. Kennedy had covered all the key ideas about *color* except the idea "color by transmission." From Mr. Kennedy's perspective, "color by transmission" was not a key idea because what students saw the most was "colors by reflection" rather "color by transmission":[3]

> Because that, I think that basically we see colors are mostly by reflection, not by transmission. And I saw that color transmission just sort of passing and said that for most objects, if they are transparent, that color they reflect, we are also

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[3] The terms "color subtraction" and "color mixing by subtraction" or "color addition" and "color mixing by addition are exchangeable.

> to say that there is a color transmitted. I don't think it is worth my time to focus on the few exceptions....I don't spend, as you know that, much time on color transmission. Because 99 percept of what they observe is going to be color subtraction. (IN, 5/29)

To conclude the analysis, in the case of Mr. Kennedy, "the combination of white light," "color by reflection," "color mixing by subtraction," and "color mixing by addition" are the four key ideas in the teaching of *color*. "Color by reflection," "color mixing by subtraction," and "color mixing by addition" are formulated through the analytic analogue consisted of "the combination of white light," "reflection," "absorption," "primary colors," "secondary colors," and "complementary colors."

The Case of Mr. Barnes

I. Key ideas about *Color* in *Merrill Physics*

In the text *Merrill Physics*, *color* is discussed in the section 16.2 "Light and Matter". Key ideas about *color* include 1) "transparent, translucent, or opaque," 2) "the combination of white light," 3) "the formation of color by addition of light," and 4) "the formation of color by subtraction by pigments or dyes."

1. Transparent, translucent, or opaque. This idea is summarized as "materials may be characterized as either transparent, translucent, or opaque depending on the amount of light they reflect, transmit, or absorb" (pp. 343). "Reflection, absorption," and "transmission" are three

important concepts or terms in formulating this idea:

> Objects can be seen clearly through air, glass, some plastics, and other materials. These materials transmit light waves and are called **transparent** materials (emphasis original). Other materials, such as frosted glass, transmit light but do not permit objects to be seen clearly through them. These materials are called **translucent**....Materials such as brick transmit no light. They absorb or reflect all the light waves that fall on them. These materials are called **opaque**....(pp. 336)

2. The combination of white light. This idea is stated as "white light is a combination of the spectrum of colors, each having a different wavelength [or frequency]" (pp. 343). Like *Conceptual Physics*, *Merrill Physics* introduces this idea through recapitulating Newton's investigation of *color* in the history:

> ....In 1666, the 24-year-old Isaac Newton did his first scientific experiments on the colors produced when a narrow beam of sunlight passed through a prism. Newton called the ordered arrangement of colors from violet to red a **spectrum**....he allowed the spectrum from one prism to fall on a second, reversed prism....a spot of **white** light was formed. After more experiments, Newton convinced himself that white light is composed of colors. We now know that each color in the spectrum is associated with a specific wavelength of light...(pp. 337)

3. The formation of color by addition of light (or color mixing by addition). The text summarizes this idea as "white light can be formed by adding together the primary light colors, red, blue, and green" (pp. 343). "The combination of white light" and "primary colors" are the important concepts or terms in the formulation of this idea:

> While light can be formed from colored light in

> a variety of ways. For example, if correct intensities of red, green, and blue light are projected onto a white screen...the screen will appear white. This is the additive process....For this reason red light, green light, and blue light are called the **primary colors** of light. The primary colors can be mixed by pairs to form three different colors. Red and green light together produce yellow light. Blue and green light produce cyan, and red and blue light produce magenta.... (pp. 338)

4. The formation of color by subtraction by pigments or dyes (or color mixing by subtraction). The text summarizes this idea as "the subtractive primary colors, cyan, magenta, and yellow, are used in pigments and dyes to produce a wide variety of colors" (pp. 343). Important concepts or terms in expounding this idea include "the combination of white light," "reflection," "absorption," "primary pigments" and "secondary pigments." As the text describes,

> The absorption of light forms colors by the subtractive process. Molecules in pigments and dyes absorb certain colors from white light. A pigment that absorbs only one color from white light is called a **primary pigment**. Yellow pigment absorbs blue light and reflects red and green light. Yellow, cyan, and magenta are the primary pigments. A pigment that absorbs two primary colors and reflects one is a **secondary pigment**. The secondary pigments are red (absorbs green and blue light), green (absorbs red and blue light), and blue (absorb red and green light)....(pp. 339-340)

The formulation of the three type 1 ideas, "transparent, translucent, or opaque," "color mixing by addition," and "color mixing by subtraction" can be displayed as in Figure 4.6. The analytic analogue for these three ideas consists of "the combination of white light"

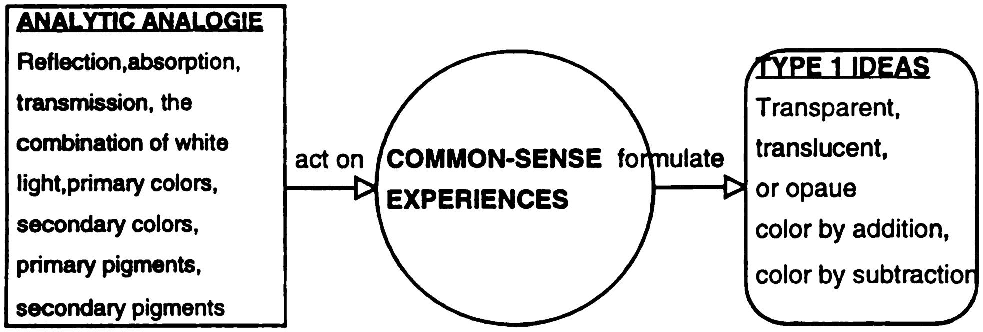

Figure 4.6 - The formulation of type 1 ideas about *color* in *Merrill physics*

"reflection," "absorption," "transmission," "primary colors," "secondary colors," "primary pigments," and "secondary pigments."

II. The teaching of *color* by Mr. Barnes

Color was taught over a period of three lessons. However, Mr. Barnes didn't devote the three lessons entirely on *color*. In each of the lessons, he spent some time on explaining other optical concepts and helping students make concept maps for the unit "Light". Therefore, in analyzing these three lessons, I only focused on describing and interpreting the three segments which were related directly to color: 1) explanations and observations of "color by reflection" and "color by transmission" in the classroom; 2) demonstrations and observations of "color by reflection" and "color mixing by addition" at the auditorium; and 3) defining "primary colors, secondary colors, primary pigments, secondary pigments, and complementary colors."

1) Explanation and observations in the classroom: "color by reflection" and "color by transmission"

The first segment was about Mr. Barnes' explanations and students' observations of "color by reflection" and "color by transmission." These two ideas were formulated through observing and interpreting several phenomena created in the classroom with reference to "the combination of white light," "reflection," "absorption," and "transmission."

In the classroom, there were a small light bulb, and many small pieces of fiber with a variety of colors on each of the six lab tables. "I would like you to jot down the objectives for the supplementary booklet," Mr. Barnes said, and he began to write on the backboard:[4]

1) Explain the following in terms of vibrations, atoms, and energy. a) U-V on glass; b) How and why visible light is transmitted through glass; c) I-R on glass.

2) Explain the difference between aunumbra and peumbra and find examples.

3) a) Discuss particle vs. wave theory for light. b) Give example for each.

4) Explain the photo-electric effect in terms of photos and energy.

5) What is polarization? Of what practical use is it?

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[4]Like Mr. Kennedy, Mr. Barnes provided each student a supplementary booklet (or study packet). It consisted mostly photocopies of some pages from the text *Conceptual Physics*.

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6) Explain colors of materials in terms of reflection, absorption, and transmission,

He said again, "Okay, what I like you to see is page 7 on the supplemental booklet."

"Page 7" was a condensed photocopy of pages 440 to 403 from the text *Conceptual Physics*, which were about "color by reflection" and "color by transmission." The page in the booklet, the objective 6) on the board, and the light bulb and pieces of colored fiber on each lab table convinced me that what he was going to teach were "color by reflection" and "color by transmission."

Mr. Barnes lifted up a small piece of blue transparency with his right hand and closed one eye, staring at a fluorescent tube on the ceiling. He said, "I could only see blue light." Then he explained that white light has all kinds of wavelengths, consisting of seven basic colors, and that the blue transparency absorbed longer wavelengths and allowed shorter ones to pass through. Then he turned to look at the red sweatshirt of a girl who was sitting in the second row through the transparency, and he said, "I saw she was wearing a black sweatshirt." He explained that the red sweatshirt absorbed all wavelengths except red, and that the transparency absorbed the red color reflected from the sweatshirt, and transmitted nothing.

Following the explanation, Mr. Barnes told students that what he wanted them to do was, first, to use some color filters to look at different colored objects in the s

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classroom (e.g., the red cover of the physics textbook, a sweatshirt, and pieces of colored fiber on the lab tables), and second, to use a colored plastic wrap to cover the small light bulb completely and observe its effect through different color filters. He passed each student a color filter (a small piece of colored transparency). He asked them to think about what color was absorbed by the colored object, what color was reflected by the object, and what color was transmitted or absorbed by the color filter.

Students were divided into six small groups (3 or 4 persons in each group), and each group worked around a lab table. Following Mr. Barnes' instruction, they looked at textbooks, a sweatshirt, and different pigments through different color filters. By the time the students had covered the small light bulbs with colored plastic wraps, and turned on the light bulbs. Mr. Barnes turned off all the light in the classroom. Again, he reminded them that they should think about the result in terms of reflections, absorption, and transmission.

2) Demonstrations at the auditorium: "Color by reflection" and "color mixing by addition"

The second segment concentrated on the ideas of color by reflection and color mixing by addition. These two ideas were formulated through observing and interpreting a variety of demonstrations in the school auditorium with reference to "the combination of white light," "reflection," and "absorption."

"We are going to the auditorium to see the effects of color filters, the combination of different colored lights, and the effects of a colored light shining on different colored papers," said Mr. Barnes in front of all students. Instantly, I guessed what he was going to teach were the ideas "color by transmission," "color mixing by addition," and "color by reflection," because these three ideas seemed to connect respectively with the phrases, "the effects of color filters," "the combination of colored lights," and "the effects of colored light shinning on different colored papers."

My guess was partially confirmed by what I actually saw in the school auditorium. Mr. Barnes only focused on "color by reflection" and "color mixing by addition." After entering the auditorium, Mr. Barnes had all students sit in the front audience seats. The first demonstration highlighted the effect of light source on the color of an object. He asked the stage assistant in the control room to turn on the white light. Instantly, a huge beam of white light from the back was shining on the stage. "Look! white light is shining, there is a huge blue curtain on the stage," he said, "Now I have yellow light come in, look what happens." He added, "We can make it happen through a yellow filter." As he signaled the stage assistant, immediately, the beam of white light became yellow, whole stage became yellow, and the curtain looked like green. He asked, "Look at the curtain....Why does it looks green?" He suggested, "Think about what color was reflected, and what color was absorbed."

The subsequent demonstrations, in line with the first two demonstrations, assured me further that what he was trying to teach was "color by reflection." These demonstrations emphasized both the effect of a light source and the natural color of an object--through reflection and absorption--upon the appearance of the color of the object to our eyes. Mr. Barnes had the assistant turn on four different colored spot lights (red, yellow, green and white), and had all students come up to the stage. "First let's look at what we can get by putting different colored papers under lights of different colors, and then let's see what color your sweaters get under each of these different colored lights." Mr. Barnes divided students into small groups, and then distributed several pieces of colored paper to each group. Following his instruction, four groups of students (each group had about five or six students) were working on the stage. Some students first placed pieces of colored paper under a particular colored spot light to observe their colored effects, and then let their sweaters be exposed to the spot light to observe the colored effects. They tried all different spot lights--red, yellow, green and white--in turn.

The last demonstration at the stage was evidently for the idea, "color mixing by addition." Mr. Barnes asked the assistant to open two spot lights. Two spot lights--one was red and the other was green--came from the top to the stage, combining together to become yellow light. "Look!" he asked, "two lights are coming down, one blue and one red, then combine together, why does it becomes yellow?" He moved on to ask the assistant to have other two spot lights--one was blue and the other was red--shine on the stage. "Ok, now blue light and red light combine together, look what color we get." He suggested, "Let's think about it in term of addition of different colors of light."

3) Learning "primary colors, secondary colors, complementary colors, primary pigments, and secondary pigments"

The third segment was about Mr. Barnes' having students learn about "primary colors, secondary colors, complementary colors, primary pigments, and secondary pigments" which were essential for the ideas of color mixing by addition and color mixing by subtraction.

Mr. Barnes started the lesson by asking students to define "primary colors, secondary colors, complementary colors, primary pigments, and secondary pigments":

> OK! A couple of things. First of all, what is primary? what is secondary? You should distinguish the answers to me. Raise your hands....What I am talking about is, what are primary and secondary

> colors, what are complementary colors, what are primary pigments and secondary pigments? I want you to define the terms in your own words. (FN, 3/14/96)

After having a couple of students define these terms, Mr. Barnes suggested that they should be able to explain what they had observed at the school auditorium in terms of absorption, reflection, primary colors, secondary colors, complementary colors, primary pigments, and secondary pigments through reading the text and supplemental materials:

> Yesterday we went down to the auditorium. We saw certain colors were absorbed, and certain colors were reflected. We also saw the combination of different colored lights. If you cannot explain what you had seen, you should read page 338 and 339 carefully. Also don't forget to read the supplemental booklet. (FN, 3/14/96)

Page 338 and 339 in *Merrill physics* explained the ideas "color mixing by subtraction" and "color mixing by addition," and the terms "primary colors," secondary light colors," "complementary colors," "primary pigments," and "secondary pigments." The pages related to *color* in the supplemental booklet were actually composed by some photocopies of the text *Conceptual Physics*.

3. The Key ideas about *color*: The case of Mr. Barnes

As revealed from the above analysis of the three segments, the key ideas about *color* in teaching include "color by reflection," "color by transmission," "color mixing by addition," and "color mixing by subtraction."

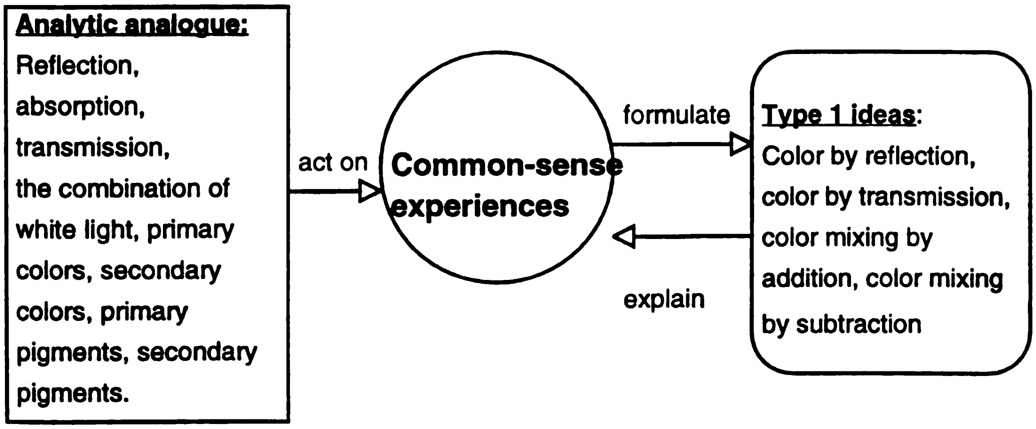

Figure 4.7 - The formulation of type 1 ideas about *color* by Mr. Barnes

Figure 4.7 displays the formulation of these four key ideas. The analytical analogue for these ideas consists of "the combination of white light," "primary colors," and "secondary colors," complementary color," "primary pigments," and "secondary pigments." They deal with a range of common-sense experiences created by demonstrations or experiments.

These four key ideas and their analytical analogue were consistent mostly with what he told me about the key ideas about *color* he intended to teach. Before his teaching the topic, in a conversation I asked him what key ideas are in teaching *color*. He refereed me to the objective sheet, telling me that he would cover all the ideas and terms contained in the six objectives:

> 1) Define each of these terms: transparent, translucent, opaque. (<u>text</u>: p. 326; 2.1 p. 342; #10 p. 343)
>
> 2) With reference to a color spectrum, tell: (a) what it is (b) how it is produced (c) what it

proves. (<u>text</u>: 337 ; #11 p. 343)

3) Differentiate between primary, secondary, and complementary colors of light. (<u>text</u>: p. 338-343)

4) Differentiate between primary and secondary pigments.
(<u>text</u>: p. 338-343)

5) Contrast light and pigments with respect to primary and secondary. (<u>text</u>: p. 338-343)

6) Explain the formation of color by: 1 -- addition of light; 2 -- subtraction by pigments or dyes. (<u>text</u>: p. 338- 343)

These objectives were developed for students to read the text *Merrill Physics* before or after class. The numbers indicated what pages they could find the ideas or terms. In addition, he told me that he also had objectives for students to read the supplementary booklet which he would put on the board later. For instance, as already showed in the first segment of his teaching, the objective related to *color* was, "Explain colors of materials in terms of reflection, absorption, and transmission."

Part Two: *The Speed of Light*

In kinematics, *velocity* or *speed* is a type 1 idea. How fast a macroscopic object travels can be described by reference to the concept of velocity or speed. *Velocity* or *speed* enables the classification and differentiation of a variety of macroscopic objects in the universe in term of the distance which an object moves in one second. *The speed of light* is the maximum speed in the universe.

The Case of Mr. Kennedy

I. *The speed of light in Conceptual Physics*

In *Conceptual Physics*, *the speed of light* involves only one idea which is stated as, "Light has a speed of 300 000 km/s in a vacuum, and lower speeds in matter" (pp. 397). The formulation of this idea in the text involves a recapitulation of the history of the measurement of the speed of light.

Conceptual Physics first introduces the earliest ideas about "how fast light can travel" and "how the speed of light could be measured":

> It was not known whether light travels instantaneously or with finite speed until almost the end of the seventeenth century. Galileo had tried to measure the time at light beam takes to travel to a distant mirror and back, but the time interval--if one existed at all--was so short he couldn't begin to measure it. Others tried the experiment at longer distances with lanterns they blinked on and off between distant mountain tops. All they succeeded in doing was measuring their own reaction times. (pp. 383)

Next it presents the first successful measurement by Olaus

Roemer in the seventeenth century:

> Experimental evidence for the first successful measurement of the speed of light was supplied by the Danish astronomer Olaus Roemer about 1675. Roemer made very careful measurements of the periods of Jupiter's moons. The innermost moon, Io, is visible through a small telescope and was measured to revolve around Jupiter in 42.5 hours. Io disappears periodically into the shadow of Jupiter, so this period could be measured with great precision....(pp. 384)

The last measurement that *Conceptual Physics* discusses is the most famous measurement conducted by Albert Michelson in the Nineteenth Century, in which the value of *the speed of light* can be rounded off to 300,000 km/s:

> The most famous experiment measuring the speed of light was performed by the American physicist Albert Michelson in 1880....Light from an intense source was directly by a lens to an octagonal mirror initially at rest. The mirror was carefully adjusted so that a beam of light was reflected to a stationary mirror located on a mountain 35 km away, and then reflected back to the octagonal mirror and into the eye of an observer. The distance the light had to travel to the distant mountain was carefully surveyed, so Michelson had only to find the time it took to make a round trip. He accomplished this by spinning the octagonal mirror at a high rate... Michelson's experimental value for the speed of light was 299 920 km/s, which we round off to 300 000 km/s. Michelson received the 1907 Nobel prize in physics for this experiment. He was the first American scientist to receive the prize. (pp. 384-385)

In sum, *Conceptual Physics* introduces the idea, "light has a speed of 300 000 km/s," through recapitulating the history of the measurement of the speed of light. In some degree, it can be said that *Conceptual physics* illustrates two ideas, "how fast light can travel" and "how the speed of light was measured historically," for *the speed of light.*

II. <u>The teaching of *the speed of light* by Mr. Kennedy</u>

Mr. Kennedy didn't devote an entire lesson to *the speed of light*. Therefore, rather than presenting the whole lesson, I only described and interpreted the instructional events related directly the topic. The analysis shows that instead of adapting the historical approach from the text, Mr. Kennedy concentrated on helping students grasp the meaning of the number "300,000 km/s" by providing examples, analogies, and questions which seemed to be very meaningful to the students.

Mr. Kennedy started the topic with a question on the overhead. The question involved a comparison of the speed of light (i.e, radio wave) and the speed of sound:

> A radio program is broadcast from an open platform in Portland, Maine. Who hears the words and music first; a listener 200 ft from the platform in Portland, Maine, or a listener at his radio receivers in Portland, Oregon, 3000 miles distant? Explain.

On the board, he first demonstrated how to calculate the time that "words" and "music" took to reach the listener 200 feet from the platform:

$$t = d/v = 200 \text{ ft}/1100 \text{ ft/s} = .18 \text{ s}$$

"How about the person in Portland, Oregon?" As he asked, he pointed students to the chart of spectrum which was hung on the upper right hand side of the classroom. "Light is an electromagnetic vibration. Radio wave is a light wave with extremely high frequency. Visible light is in the middle of the spectrum, a very narrow band," and he told students that people call it as "speed of light" due to the historical reason: "Light had been studied since a very early age, and the speed of light had been measured in the sixteen century."

He wrote down value of the speed of light on the board:

$C = 3 \times 10^{8}$ m/s = 186,000 miles/s

And he turned to calculate the time taken by radio waves to reach the second listener:

$t = d/C = 3000$ miles/186 000 miles/s = 0.016 s

After this example, Mr. Kennedy said, "It is very hard to have a feeling of how fast it is, 186,000 miles/s. So people turn to use analogies. Let's say you jump in your car in 2/3 second. It takes less than 0.02 second for light to travel from Maine to Oregon." He asked students to open their packets. He helped students work through other four analogies or examples in their packets,

1) It takes 8 minutes for light to travel from sun to reach us. Let's say your car travels at 45 miles/hr and you want to travel to sun using cruse control. It takes 193 years to reach the sun. Let's say an airplane flies at 900 miles/h. It takes 21 years to reach the sun.

2) Light can make 18.000 round trips from San Francisco to New York in one second.

3) The star nearest us, except for our sun, is Proxima Centaurus. It is twenty-five trillion miles away. How long does it take light to reach us from this celestial neighbor? Express answer in years. If Proxima Centaurus "went out" three years ago, would we know it yet?

4) Sirius, the brightest star we can see in the sky, is the fifth closest star to us. It is "only" 8.8 light-years away. How far it this in miles?

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III. Key idea about *the speed of light*: The case of Mr. Kennedy

As revealed from the above episode, Mr. Kennedy concentrated on helping students make sense of "how fast light can travel" through providing a rich set of analogies, examples, or questions. In our conversation after class, he told me that the number 3 x 10^8 was "meaningless" to the high school students unless they could see a lot of examples and analogies.

While *Conceptual Physics* illustrates the two ideas, "how fast light can travel" and "how the speed of light was measured historically," through recapitulating the history about the measurement of *the speed of light*, Mr. Kennedy only taught "how fast light can travel" through providing examples, analogies, and questions. The time limit in the semester determined that he didn't teach "how the speed of light was measured historically". As he explained,

> Some years I do [teach "how the speed of light was measured historically]. Yes! I tell you basically, I just spent a day, I used to talk about Michelson's method, also I talk about Fizeau's method, or one of the classic methods of measuring the speed of light. Again, we sort...we basically looking at last year calendar, we were about two weeks behind....So, anyway, we, what you are going to do. And we decided we won't spend that extra day, on some of the classic measurements of the speed of light....(IT-Kennedy, 5/29/96)

He also indicated that teaching "how the speed of light was measured historically" was to help students understand how "something that fast" could be measured:

> Just, just to show how they measure something that fast, using equipments of the time, okay. Be easy to measure today, now we have electronic equipments. But this was measured before they had electronic equipments. It is so fast either you had to measure time epoch extremely short, or let light travel a distance, you know, commute a great distance, so the time ellipse will be enough to enable you to measure with classic device...(IT-Kennedy, 5/29/96)

Therefore, in the case of Mr. Kennedy, "how fast of light can travel" and "how the speed of light was measured historically" are two key ideas for the topic *the speed of light*. The teaching of first idea involves the use of analogies, examples, or questions. The teaching of the second idea might involve a recapitulation of the history of the measurement of *the speed of light*.

The Case of Mr. Barnes

I. *The speed of light in Merrill Physics*

In *Merrill Physics*, the basic idea in the topic *the speed of light* is, "light in a uniform medium travels in a straight line at a speed of 3 x 10^8 m/s in a vacuum" (pp. 343). Like *Conceptual Physics, Merrill Physics* illustrates this idea through a historical presentation.

The introduction of *the speed of light* begins with the beliefs about how fast light can travel and Galileo's measurement before the seventeenth century:

> Before the seventeenth century, most people believed that light traveled instantaneously. Galileo was the first to hypothesize that light had a finite speed and to suggest a method of determining it. His method, however, was not

> sensitive enough, and he was forced to conclude that the speed of light was too fast to be measured at all over a distance of a few kilometers. (pp. 331)

Following Galileo's measurement, the text introduces the measurement conducted by Ole Roemer:

> ....The Danish astronomer Ole Roemer (1644-1710) was the first to determine that light did travel with a measurable speed. Between 1668 and 1674, Roemer made 70 careful measurements of the 42.5-hour orbital period of Io, one of the moons of Jupiter... He recorded the times when lo emerged from behind Jupiter and found that the period varied slightly. The variation was as much as 14 seconds longer when Earth was moving away from Jupiter and 14 seconds shorter when Earth was approaching Jupiter. He concluded that as Earth moved away from Jupiter, the light from each new appearance of lo took longer to travel the increasing distance to earth... Roemer's value of 22 minutes gives a speed of 2.2×10^8 m/s...(pp. 331)

The next experiment *Merrill Physics* presents is the most famous one conducted by Albert Michelson:

> Although many laboratory measurements have been made, the most notable was a series performed by the American physicist Albert A. Michelson... Between 1880 and the 1920s, he developed Earth-based techniques of measuring the speed of light. In 1926, Michelson measured the time light required to make a round trip through a pipe from which all air had been removed. The pipe was constructed between California mountains 35 km apart. Michelson's best result was $2.997996 \pm 0.00004 \times 10^8$ m/s. For this work, he became the first American to receive the Nobel prize. (pp. 331)

The text ends with the discussion through introducing contemporary methods for its measurement:

> The development of the laser in 1960 provided new methods of measuring the speed of light. As with other electromagnetic waves, the speed of

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> light is equal to the product of its frequency and wavelength. The speed of light in a vacuum is such an important and universal value that is can be counted with extreme precision using the time standard provided by atomic clocks... As a result, in 1983 the international committee on Weights and Measurements decided to make the speed of light a defined quantity....(pp. 332)

In short, like *Conceptual Physics*, *Merrill Physics* adopts a historical presentation for the idea: light travels at a speed of 3×10^8 m/s. In some sense, the topic involves two basic ideas: "how fast light can travel" and "how the speed of light was measured historically."

II. The teaching of *the speed of light* by Mr. Barnes

Like Mr. Kennedy, Mr. Barnes didn't use an entire lesson to teach *the speed of light*. Here I only focused on describing and interpreting the instructional event that was related directly to the topic.

"I would like you to jot this down in your notebook!" As Mr. Barnes spoke, he wrote down "speed of light = 186,000 mi/sec" on the board. "I want to impress you how fast it is," he continued, "In the United States of America, the distance of coast to coast is 3,000 miles and a round trip is 6,000 miles." He also drew a diagram on board to illustrate these distances. He asked, "How many round trips can light take in one second?"

In front of the students, Mr. Barnes demonstrated how to calculate the number of round trips on board:

$$186{,}000\text{mi/sec} * 1 \text{ sec} / 6{,}000 \text{ mi} = 31$$

By showing this calculation, he said, "I would like you to know that light can make 31 round trips across the united states in one second." He emphasized, "This is what I want you to get!" Again, he emphasized, "You get the idea how fast light is. And now you begin to appreciate the speed of light."

Following the calculation, Mr. Barnes told students, "Now you know the difficulties people have in measuring the speed of light," and "You can measure the speed of sound, but you cannot use the same method to measure the speed of light." He continued, "Look at the pages in the booklet, there were the first person, the second person, and the third person who had measured the speed of light." "The third person, Michelson was very famous and very well known." He emphasized, "Look at the techniques and methods these three persons used," and he added, "Something in physics is extremely not easy. Light travels so fast, it is very difficult to measure."

III. The Key ideas about *the speed of light*: The case of Mr. Barnes

As revealed from the episode, Mr. Barnes focused his teaching on helping students make sense of "how fast light can travel" through providing an example. In addition, he had students learn about "how the speed of light was measured historically" by themselves.

"How the speed of light was measured historically" is a key idea in his teaching *the speed of light*. This is evident in his belief that some high school students were interested in knowing how the speed of light was measured:

> Well, as soon as you tell them, how, you know the speed of light 186,000 miles/sec. They know it is a big number. But they don't know how big it is. And the next question is, how someone ever figured that out? How they measured it. They used the stop watch, they used the stop watch, and turn off and on switch. No! That is what we did in mechanics with cart, you have a cart going down a table, add a photo gate timer, and we have a stop watch, we start it hear and stop it here....Yes, for sound, maybe, why can't we do it for light. It goes away too fast. Wow, how do we know it go on 186,000 mile/sec? Well, there were some men that did some experiments that tried to find out. So let's look at, I add a little bit of history. So the velocity, just at the standpoint of interesting. How far does light go and how do we know. So kids, I found over the years would ask these questions. How do we know that fast?. That is really fast.... Kids may come up with that. How do we know that fast? So, from now on, I just, I just present these to students. They didn't asked about Roemer's result, but over the years they asked me, how do we know light goes that fast? Who measured it? How do we know? Did someone just made it up? What kind of instrument did they use? Anything right on the lab here... So, they want to know. That is a very special velocity, very special. (IT-Barnes, 4/18/1996)

It is worth pointing out that while "how the speed of light was measured historically" was a key idea, Mr. Barnes didn't explain it explicitly in the classroom. Like the strategy he used in teaching *color*, he guided students to read the text *Merrill Physics* (pp 313-332) as well as the supplementary materials (i.e., the booklet) about the measurements of light (taken from *Conceptual Physics*).

In short, in the case of Mr. Barnes, "how fast light can travel" and "how the speed of light was measured historically" are the key ideas for *the speed of light*. The first idea was conveyed to students through an example. The second idea was taught through guiding students to read the history presented in the texts.

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Part Three: *Light Interference*

The Case of Mr. Kennedy

I. *Light interference in the text Conceptual Physics*

In discussing the topic *light interference*, *Conceptual Physics* first presents a summary for the ideas "constructive interference" and "destructive interference" which have already been introduced in previous chapters on "water waves" and "sound waves":

> The idea of wave interference was introduced in Chapter 25, and applied to sound in Chapter 26. The idea is important enough to summarize here before applying it to light waves....
>
> If you drop a couple of stones into water at the same time, the two sets of waves that result cross each other and produce what is called an *interference pattern*. Within the pattern, wave effects may be increased, decreased, or neutralized. When the crest of one wave overlaps the crest of another, their individual effects add together; this is *constructive interference*. When the crest of one wave overlaps the trough of another, their individual effects are reduced; this is *destructive interference*. (pp. 462)

Next the text introduces Thomas Young's interference experiment, and suggests that the interference patterns revealed by the experiment can be explained in terms of "constructive interference" and "destructive interference":

> In 1801 the British physician Thomas Young performed an experiment that was make him famous... Young discovered that when **monochromatic** light--light of a single color--was directed through two closely spaced pinholes, fringes of brightness and darkness were produced on a screen behind. He realized that the bright fringes of light resulted from light waves from both holes arriving crest to crest [constructive interference--more light]. Similarly, the dark areas resulted from light waves arriving trough to

light that Huygens had proposed earlier. (pp. 463)

"Constructive interference" and "destructive interference" are at the type 2 level because the entity (i.e, the interaction of light waves) is unobservable and yet has an empirical consequence--that is, the interference patterns. "Water wave interference" or "sound wave interference" is the source analogue for developing representations for "constructive interference" and "destructive interference." I use Figure 4.8 to display this formulation of type 2 ideas about *light interference*.

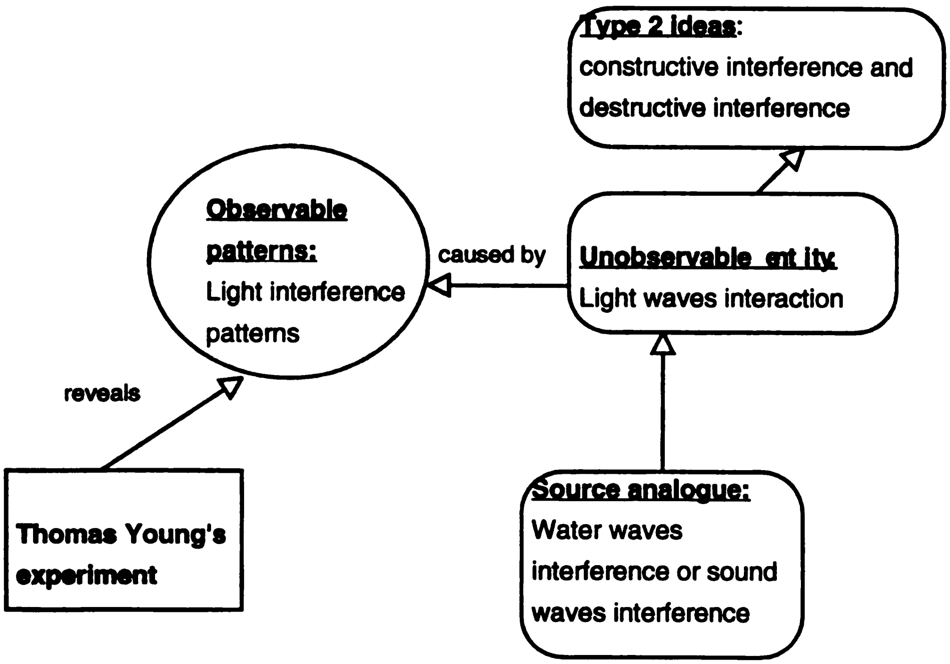

Figure 4.8 - The formulation of type 2 ideas of light interference in *Conceptual physics*

II. <u>The teaching of *light interference* by Mr. Kennedy</u>

I didn't have the chance to observe how Mr. Kennedy taught *light interference*. He didn't teach the topic for he was two weeks behind the schedule of the semester. What I did was to interview him about the teaching of *light interference*.

The first question I asked was, "What are the key ideas about *light interference* you would like students exposed to in teaching the topic?" His response suggested that "constructive interference," "destructive interference," and "coherence" (i.e., "lock in phases") are the key ideas:

> Key ideas again are that light waves, just like any other type of waves. Then, there is constructive interference, when crests meet crests, and destructive interference. Ah, and go into why you don't ordinarily observe it because the wavelength of light is so small. And when two light sources, are, you have two light sources close together, basically phases are not locked together. So basically the nodal and anti-nodal lines are constantly shifting with respect to each other, so you just see an average....You have a single light source go through two slits, so you break the same...light wave into two parts, so they lock in phase with respect to each other, so you can observe a whole stationary pattern. (IT-Kennedy, 5/29/96)

My second question was, "How do you approach the teaching of *light interference*?" He indicated that he started with a demonstration with laser to have students see the interference fringes:

> Well, basically we get up some little prepared slices we shine a laser light through it, I let them see the interference fringes, on a screen.... I take a laser, I darken the room, I have a slice with couple of slits in it, I shine a laser light

> through it, form a interference pattern. And they can see the bright and dark bands, always close to each other....(IT-Kennedy, 5/29/96)

Following this response, I asked Mr. Kennedy, "What do you want students to learn for the demonstration?" He suggested that students should see that the patterns in light interference--like the patters in water waves interference or sound waves interference--were the results of "constructive interference" and "destructive interference." As Kennedy Stated,

> Okay, I want them by looking at the pattern formed by the laser, to go back what they saw on a ripple tank, and what they observed with sound, to realize that the patterns are different, but they are all the results of constructive interference and destructive interference... I will take the ripple tanks down and put them in there. Ripple tanks, the old PSSC textbook that, they use ripple tanks a lot...they are very good for illustrating wave properties. (IT-Kennedy, 5/29/96)

My fourth question was, "Are you helping students make connection between light interference and water waves interference and sound waves interference?" His reply further indicated that teaching *light interference* is based upon "water waves interference" or "sound waves interference":

> I think that is a big part....that is a big part of. There is no difference, just scale. It is easy for them to visualize water waves so, than for them to visualize light waves. But right I think one build on the other. (IT-Kennedy, 5/29/96)

To summarize, the interview revealed that "constructive interference," "destructive interference," and "coherence" are the three key ideas in teaching *light interference* for high school students by Mr. Kennedy. These ideas are formulated through a laser demonstration, based upon the model of water waves interference or sound waves interference. Figure 4.9 summarizes the formulation of these three ideas.

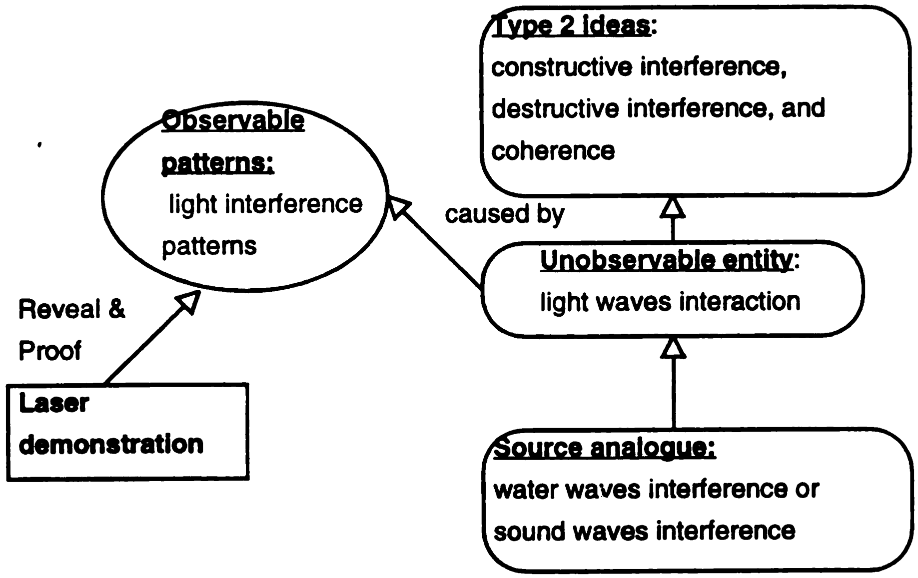

Figure 4.9 - The formulation of type 2 ideas about *light interference* by Mr. Kennedy

III. Key ideas about *light interference*: The case of Mr. Kennedy

Evidently, Mr. Kennedy's using "water waves interference" (or "sound waves interference") to teaching *light interference* is quite compatible with the approach depicted in the text *Conceptual Physics*. In other words, "water waves interference" (or "sound waves interference") is the source analogue for developing representations for "coherence," "constructive interference" and "destructive interference."

However, there are two differences in the key ideas between his teaching and the text. While Mr. Kennedy viewed "constructive interference," destructive interference," and "coherence" as the key ideas for the topic, *Conceptual Physics* only emphasizes "constructive interference" and "destructive interference". *Conceptual Physics* recapitulates Thomas Young's experiment as the evidence for light interference, and yet Mr. Kennedy used a laser demonstration as the evidence.

The Case of Mr. Barnes

I. *Light interference in Merrill Physics*

In "Chapter 19 review", *Merrill Physics* summarizes *light interference* as "Interference between light diffracted from two closely-spaced narrow slits causes an interference pattern to appear on a distant screen" (pp. 403). An examination of the text shows that "coherence," "constructive interference," and "destructive interference" are the key ideas, and that these ideas are formulated through a recapitulation of the famous Thomas Young's experiment.

Merrill Physics first suggests that light interference fringes result from "constructive interference" and "destructive interference" through introducing Young's experiment:

> ....Young's experiment gave additional evidence of the wave nature of light. Young allowed light to fall on two closely spaced narrow slits. The light passing through each slit was spread out, or diffracted. The spreading light from the two slits overlapped. When the light fell on an observing screen, the overlap did not produce extra light, but a pattern of bright and dark bands called **interference fringes**. Young explained that these bands were the results of constructive and destructive interference of the light waves from the two slits. (pp. 392)

Next *Merrill Physics* introduces "coherence"--that is, the condition of light interference that two light waves are in the same wavelength and are in the same phase:

> Young used a monochromatic...light source, one that emits light of only one wavelength. He placed a narrow silt in front of the source. The slit allowed light from only a small part of the source to pass through. As a result, the waves were not only the same wavelength, but all were in step. That is, they were **coherent**....(pp. 392)

Next it explains "constructive interference"--that is, the interaction of two coherent light waves when their crests and crests meet and troughs and troughs meet--and "destructive interference"--that is, the interaction of two coherent light waves when their troughs and crests meet:

> ....The waves spread after passing through the single slit and fell on the double slit. The double slit acted as two sources of new circular waves....the semicircles represent wave crests moving outward from the slits. Midway between the crests are the troughs. The waves from the two sources interfere constructively at points where two crests overlap. They interfere destructively where a crest and a trough meet. (pp. 392-393)

The text moves on to point out that "constructive interference" is responsible for the bright bands in an interference pattern, and "destructive interference" is responsible for the dark banks in an interference pattern:

> When monochromatic light is used....bright bands of light appear at points where the constructive interference occurs on the screen. One bright band appears at the center of the screen. On either side of the central band are bright bands corresponding to the other points of constructive interference. Between the bright bands are dark areas located where destructive interference occurs on the screen. (pp. 393)

It is worth pointing out that while *Merrill Physics* highlights the importance of Young's experiment in introducing "coherence," "constructive interference," and "destructive interference," it doesn't mention explicitly the what source analogue is used in formulating the ideas. Figure 4.10 summarizes the formulation of these three ideas in the text.

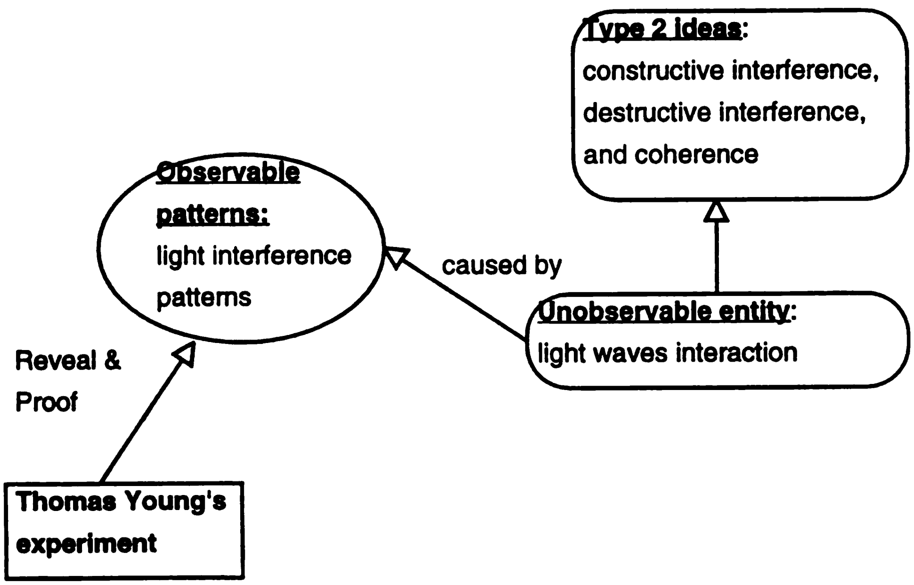

Figure 4.10 - The formulation of type 2 ideas about *light interference* in *Merrill's physics*

II. The teaching of *light interference* by Mr. Barnes

The teaching of *light interference* consisted of two lessons. The first lesson focused on two substantive ideas: "constructive interference" and "destructive interference." Its goal was to help students develop visual representations of "constructive interference" and "destructive interference." The second lesson was about measuring wavelength through a two-source light interference experiment. Since the central focus of this study is key substantive ideas, I only described and interpreted the instructional events in the first lesson.

The lesson involved three events: 1) drawing circular wave patterns on pieces of paper, 2)making connections between semicircular wave patterns and water waves interference patterns, and 3) making connections between water waves interference patterns and light waves interferences patterns.

The 1st event: drawing circular wave patterns

When I stepped into the classroom, it was not surprising for me to notice four ripple tanks on four lab tables, and many pairs of compasses on the podium. From the objective sheet I got from him yesterday, I knew that Mr. Barnes was going to introduce students to some basic ideas about *light interference* through engaging students in the following activities "a) making and analyzing semicircular interference patterns using two points sources in a ripple tank."

"OK, let's make semicircular wave patterns." Mr. Barnes begun the lesson. In front of the students, he demonstrated how to draw semicircular wave patterns on the board. He dotted down two small dots separated by a small distance to represent two points source respectively. Using a pair of compasses, he drew two sets of semicircles (see Figure 4.11).

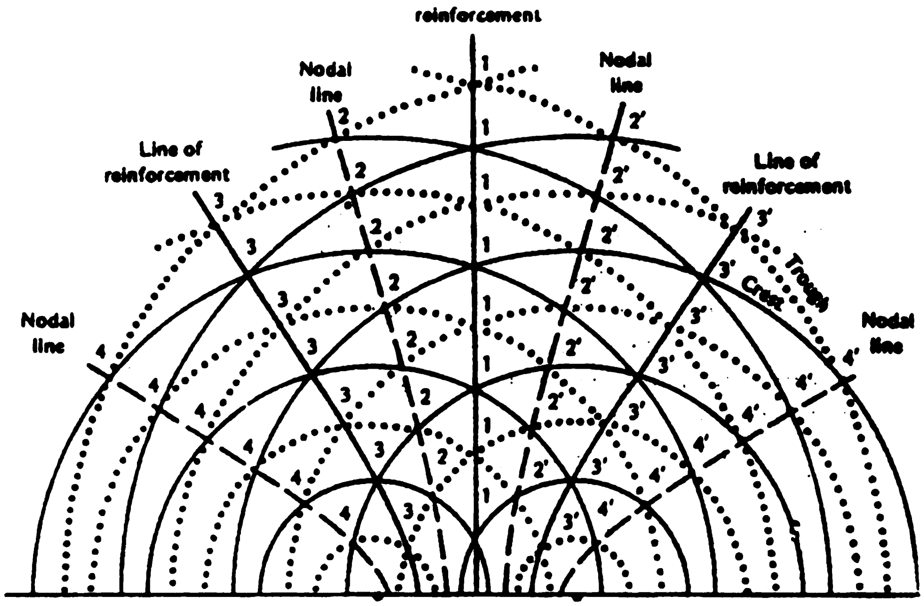

Figure 4.11 - Semicircular wave patterns

He told students that each set of semicircles represented a pattern of "crests" and "troughs" streaming out from a point source, the "crests" were shown by solid lines, and the "troughs" by dotted lines; and that the distance from one crest to the next, or from one trough to the next, represented the "wavelength."

"You should go pretty fast," he spoke immediately after his demonstration, "I start to explain these wave patterns in about five minutes." Following his suggestion, each student picked up a pair of compasses and a ruler, returned to their sits, and started to make semicircular wave patterns.

While students were busy in drawing circular wave patterns on sheets of paper, I looked at the objective sheet again. I guessed that what Mr. Barnes sought to do was to make the interaction of light waves become visualized, or make the key ideas involved in *light interference* become concrete for students through the two activities. According to the objective sheet, students were expected to "review, define/explain" the ideas of "constructive interference," "destructive interference," and "phase" and some terms that can "visualize" the ideas, such as "crest," "trough," "reinforcement," "node," and "nodal line."

My guess was confirmed by the explanation he gave after students had finished drawing semicircular wave patterns. In front of all students, he drew several solid lines to connect the points of intersection between any two "crests" or of any two "troughs" from the two different "sources" (see Figure 4.11 above). He told students that the solid lines were called "lines of reinforcement," because along each of these line two waves reinforced each other, and thus "constructive interference" occurred. Then he connected the points of intersection between the "crests" and "troughs" from the two "sources" through some doted lines. He told students that the doted line were "anti-nodal lines," and that on these lines two waves canceled each other, and thus "destructive interference" occurred.

<u>The 2nd event: making connections between semicircular wave patterns and water waves interference patterns</u>

"OK! I would like to divide you into four small groups, each group works on a ripple tank." Mr. Barnes started the second activity immediately after the explanation. He emphasized, "I want you to follow exactly the activity 2 a) and b) on your objective sheets. I would like you to make some nice connections between what you get from the ripple tank and what you just wrote." Following Mr. Barnes' suggestion, students divided themselves into four groups, each of which had about 4 or 5 students, and worked on four different ripple tanks on the lab tables.

As I looked at the objective sheet, another guess immediately emerged in my mind: what Mr. Barnes was trying to do was to have students make connections in "destructive interference" and "constructive interference" between what were represented by semicircular wave patterns on sheets of paper and what were displayed in water waves interference patterns in ripple tanks. According to the objective sheet, activity 2 involves,

> Given 2 sets of circular waves generated from 2 different point sources in a ripple tank where the water is of even depth throughout:
>
> (a) If the 2 sources are in phase, sketch the interference pattern made when waves from both sources meet each other and explain why such a pattern is formed;
>
> (b) Find out lines of reinforcement and nodal lines and find out areas of constructive interference and destructive interference.

My subsequent observation, again, confirmed my presumption. While four groups of students were working on four ripple tanks, Mr. Barnes moved from one group to another. He encouraged students to do their best to obtain a good water waves interference pattern. He commented, "The better pattern you can get, the easier you will be able to sketch the nodal lines and the lines of reinforcement."

His intention to help students make connections between the semicircular wave patterns and water waves patterns became more transparent to me, as I turned to page 4 in the supplemental booklet by following his instruction. "Let's turn to page 4 on your booklet. This page is a key to understanding what you have been doing," stated Mr. Barnes. The page was divided equally into two parts. On the left, one semicircular wave pattern, two water waves interference patterns, and two light waves interference patterns were juxtaposed, from top to bottom. On the right, there were three different diagrams of Young's experiment, each of which portrayed the experiment from a unique perspective. In particular, Mr. Barnes already used arrows to indicate the correspondence in nodal lines between the circular waves pattern, the water waves interference patterns, and the light waves interference patterns. The succeeding episode was about how Mr. Barnes helped students make the connections in the classroom.

He asked all students to come over to a ripple tank on one of the lab tables in the back of the classroom with their supplementary booklets. Immediately, the table was surrounded by a cloud of students, and some students were standing on two other tables near the ripple tank. "Look, here is probably the best water interference pattern we can get in a ripple tank." As he said, he pointed to some areas where water was at rest, and told students that they were the areas of nodal lines, and water waves were stable along the nodal lines. Then he pointed to the midway between those stable areas, told students that they were areas of lines of reinforcement, and water waves were passing through these lines with great amplitude. Mr. Barnes suggested that students should look at page 4 on the booklet. He said,

> Now you can see the connections between what you just drew on sheets of paper and what you saw from a ripple tank, I want you to understand what nodal lines are, what lines of reinforcement are, and how they can be connected with constructive interference and distractive interference....(FN. 4/24/96)

<u>The third event: making connections between water waves interference patterns and light waves interference patterns</u>

The last episode was his helping students make connections in "nodal lines" and "lines of reinforcement" between water waves interference pattern and light waves interference pattern. After the observations of water waves interference patterns in ripple tanks, Mr. Barnes asked students to go back to their seats. "Let's open your book to page 393, and your supplementary booklet to page 4." In *Merrill Physics*, page 339 presents the sketch of Young's two sources interference experiment, and pictures of light interference patterns. Page 4 in the supplementary booklet had pictures of water waves interference patterns, light waves interference patterns, and diagrams of Young's experiment.

"Thomas Young did a very important experiment in the history by providing a direct proof for the wavelike nature of light," he said. He asked students to look at the diagrams of the experiment and the interference patterns closely, and to find out the "similarities" between water waves interference patterns and light waves interference patterns on page 4 in the supplementary booklet. "I have used arrows to point out the connections between water interference patterns and light interference patterns," he said, "After you can connect the nodal lines in the ripple tank with the notal lines on light interference patterns, you should be able to understand how the dark areas were formed, and how the light areas were formed," and he suggested, "You should be able to understand dark and light areas in terms of destructive and constructive interference."

III. The Key ideas about *light interference*: The case of Mr. Barnes

As revealed from the lesson, "constructive interference," and "destructive interference" are the two key ideas in his teaching *light interference*. The formulation of these two ideas started with semicircular wave patterns, proceeded through water waves interference patterns, and eventually applied to light waves interference patterns with reference to Thomas Young's experiment. Figure 4.12 summarizes this way of formulating the two type 2 ideas.

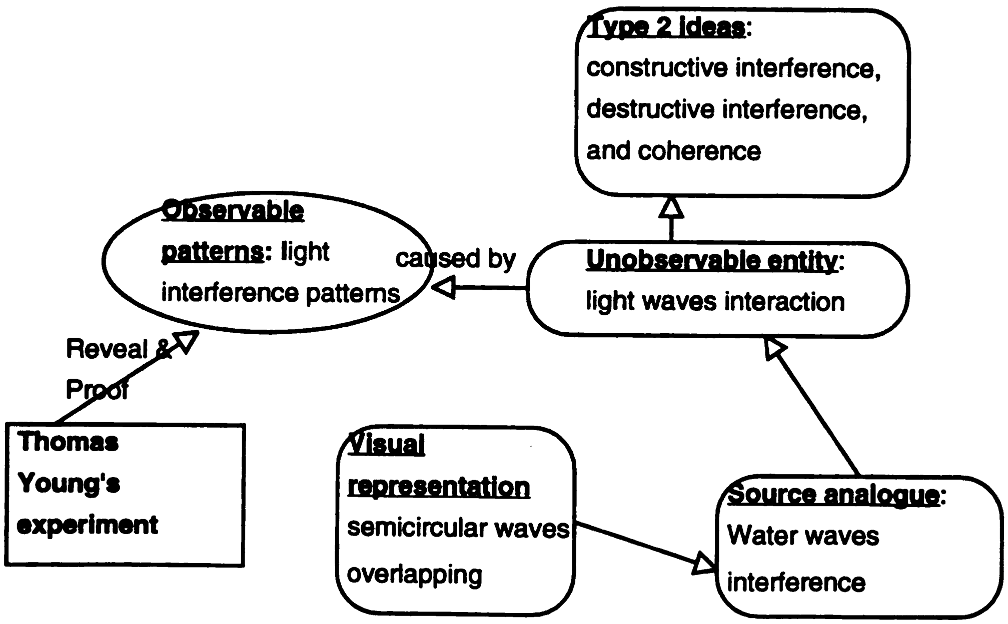

Figure 4.12 - The formulation of type 2 ideas about *light interference* by Mr. Barnes

In other words, semicircular wave patterns provide visual representations for "water waves interference". "Water waves interference is the source analogue, and Young's experiment provides empirical evidence for the ideas about *light interference*.

This way of formulating the two key ideas was consistent with what he commented on key ideas about *light interference* in the interview:

> You [students] need to understand what interference is, and what the dark areas, that we have cancellation. Now light areas, we have reinforcement. So that is why we started out with water waves, waves we can see, we can see the water waves, we can see the interference, we can see canceling....let them see constructive and destructive interference. And then eventually we go to sound, and then eventually to light, where we can't see the waves, but we can see the results. We can see the evidence. We can't see what is going on in between, we can't see the waves coming through the air....But we can see the results. We can see the evidence. We can see the light and dark bands from the Young's experiment. (IT-Barnes, 5/28/96)

It was not a surprise for me that he didn't mention those semicircular wave patterns which he had students draw on a sheets of paper. For one thing, according to our conversation after his teaching this lesson, he told me that they were some sort of "pictorial representations" for "constructive interference" and destructive interference."

Finally, I need to point out two differences in key ideas about *light interference* between *Merrill Physics* and his teaching. While "coherence" is also main idea for light interference in *Merrill Physics*, in addition to "constructive interference" and "destructive interference," Mr. Barnes seemed to mainly focus on "constructive interference" and "destructive interference." Another difference is reflected in formation of "constructive interference" and "destructive interference." The text introduces these two ideas simply through a recapitulation of Thomas Young's experiment. On the contrary, Mr. Barnes used the experiment as a piece of evidence for light interference, and developed the two ideas through drawing upon the similar ideas from the discussion on "water waves interference" or "sound waves interference."

Chapter 5

HOW THE KEY IDEAS IN TEACHING *COLOR, THE SPEED OF LIGHT,* AND *LIGHT INTERFERENCE* AT THE HIGH SCHOOL LEVEL DIFFER FROM THOSE IN THE DISCIPLINE OF PHYSICS

Based upon my analysis of the two cases of high school physics teaching in chapter four, the key ideas in teaching *color, the speed of light*, and *light interference* at the high school level can be summarized as follows:

Color. The key ideas involve "color by reflection," "color by transmission," "color mixing by subtraction," and "color mixing by addition." They are type 1 ideas formulated through the analytical analogue consisted of "the combination of white light," "primary colors," "secondary colors," "complementary colors," "reflection," "transmission," and "absorption."

The speed of light. The key ideas involve "how fast light can travel" and "how the speed of light was measured historically."

Light interference. The key ideas involve "constructive interference," "destructive interference," and "coherence." They are type 2 ideas formulated through the source analogue, "water waves interference" (or "sound waves interference").

The question this chapter addresses is, **how do the key ideas in teaching *color, the speed of light,* and *light interference* at the high school level differ from those in the discipline of physics?** I will compare the key ideas in teaching these three topics for high school students and the corresponding key ideas for prospective physicists or scientists.

Proposition 3 & 4 from my conceptual framework are crucial for this comparison. I briefly summarize these two propositions as follows (see chapter two, for a more detailed discussion),

3. Key ideas in teaching school physics or in the intellectual discipline of physics can be categorized into three theory-types (type 1, type 2, & type 3), the referents of which are relative to the possibilities of human experiences in terms of Realm 1, Realm 2, and Realm 3.

4. The development of realm 1 discourse (or type 1 theories) involves the use of analytical analogues, and the development of realm 2 discourse (or type 2 theories) involves the use of source analogues. Realm 1 discourse is grounded in the physical world, and Realm 2 discourse is grounded in Realm 1 discourse and scientific experiments.

1. *Color*

While *color* is a very important topic in teaching optics for high school students, it is usually not included in teaching optics for prospective physicists or scientists. Klein & Furtak's (1986) *Optics* discusses little about *color*. Hecht & Zajac's (1979) *Optics* provides a very small section discussing different color-generating mechanisms.[1] My interviews with the two optics professors and the two high school physics teachers support that *color* is not a topic formally discussed in college optics course (for the interviews, see chapter 6 and 7).

Although *color* is usually not included in teaching optics for prospective physicists or scientists, three concepts important in teaching *color* at the high school level, "reflection," "transmission," and "absorption," are very essential in teaching optics for prospective physicists or scientists. Accordingly, I focused on analyzing how these three concepts in teaching *color* for high school students differ from those in teaching optics for prospective physicists and scientists.

As already illustrated in chapter four, "reflection," "absorption," and "transmission" are used in formulating the four type 1 key ideas about *color*: 1) "transparent, translucent, or opaque," 2) "color by reflection," 3) "color by transmission," and 4) "color mixing by subtraction." These three concepts provide classificatory categories through which materials are characterized as either transparent, translucent, or opaque. They also provide

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[1] This section is entitled "4.4. Familiar aspects of the interaction of light and matter", pp 89-91. Hecht & Zajac's *Optics* is a very exceptional case among college optics textbooks. It "embrace the pedagogically valuable classical methods along with the major new developments, techniques, and emphasis."

classificatory categories through which our common-sense experiences related to the formation of *color* are differentiated in terms of "color by reflection," "color by transmission," "color mixing by subtraction." In other words, by acting as a set of analytical schemes, "reflection," "transmission," and "absorption" sharpen our grasp of the patterns about *color* which are implicit in our common-sense experiences.

While teaching *color* for high school students emphasizes portraying "reflection," "transmission," and "absorption" at the type 1 level--that is, using these three concepts to explain a variety of observable phenomena about *color*, teaching optics for prospective physicists or scientists concentrates on discussing "reflection," "transmission," and "absorption" at the type 2 level--that is, building representations for the realm 2 entity (i.e., the interaction of light with materials) that causes reflection, transmission, and absorption. In building representations for the interaction of light with materials, college optics uses the electromagnetic model of light as the sources analogue. Light is envisioned as a classical electromagnetic wave that obeys Maxwell's equations. A material is envisaged as an assemblage of atoms and molecules which has an internal electric charge structure. In principle, by applying Maxwell's equations and establishing associated boundary conditions which impose

restrictions on the electromagnetic fields in the materials, college optics can describe the changes in radiant energy and field amplitude of a light wave as it progresses through the materials, crossing each interface, being reflected, transmitted or absorbed (cf. Klein & Furtak, 1986; Hecht & Zajac 1979).[2]

How to develop representations for the interaction of light with materials in teaching "reflection," "absorption," and "transmission" were further illustrated by the two optics professors. Professor A suggested two different ways of representing the interaction within a stack (i.e., a stack of microscope slides) in terms of field amplitudes and boundary conditions:

> With a stack, you can think of it two ways. You can think about subsequently what goes on by setting up a field, having it reflected, and transmitted, going to another surface, having its reflection and transmission there... So you can treat that situation in terms of an infinite series of electric field amplitudes you have to solve.... Or you can do it in a situation where you totally match boundary conditions. So that is electromagnetic field boundary conditions, in terms of a incident field, totally transmitted in field, and totally reflected in field, match the boundary conditions... We deal with both ways to show what we get are exactly the same. (IT-PA, 5/22/96)

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[2] In practice, using Maxwell's equations and the associated boundary conditions to trace to progress of radiant energy and field amplitude is often an impractical task, due to the difficulty in establishing boundary conditions and solving Maxwell's equations in some rather complicated situations. In addition, the quantum theory of matter sometimes is used to justify some details of the progress.

Professor B indicated that he sought to have students see the Snell's law (the law of refraction) as a manifestation of Fresnel's equations (these are the mathematical relationships between amplitudes and phases in reflection, reflection, and refraction):

> In terms of reflection and transmission, ah, at least in the advanced optics course...my presumption is that they have already known basically, ah, the issues of, they have already seen Snell's law, before they get to me. What I try to do is to put a different beam on it. They have seen these probably in a context of some empirical laws.... how is it that Snell's law is really a manifestation of that? So when we look at reflection and transmission acrose the boundary, the way in which we do so, is from the point of view of Fresnel's equations....So again what we try to do is to, is to give them another manifestation of some fundamental physics and mathematics. And so, that is how I do it (IT-PB, 9/18/96)

He suggested further that Fresnel's equations were developed based upon Maxwell's equations and associate boundary conditions:

> Fresnel's equations, ...for the amplitude of the reflected and transmitted waves, those amplitudes are the directed consequence of Maxwell's equations in a boundary condition. So I talk about Fresnel's equations, we've already gone through the development from Maxwell's equations to give rise to these amplitudes. (IT-PB, 9/18/96).

In short, teaching "reflection," "transmission," and "absorption" for prospective physicists or scientists emphasizes constructing representations for the interaction of light with materials through establishing boundary conditions and solving Maxwell's equations.

It is important to notice that the high school text

Conceptual Physics also analyzes "reflection," "transmission," and "absorption" at the type 2 level (see chapter 4). However, the source analogue used in *Conceptual Physics* is fundamentally different from the one used in teaching optics for prospective physicists or scientists. The former is "the interaction of sound waves with tuning forks"; the later is the classical electromagnetic model of light.

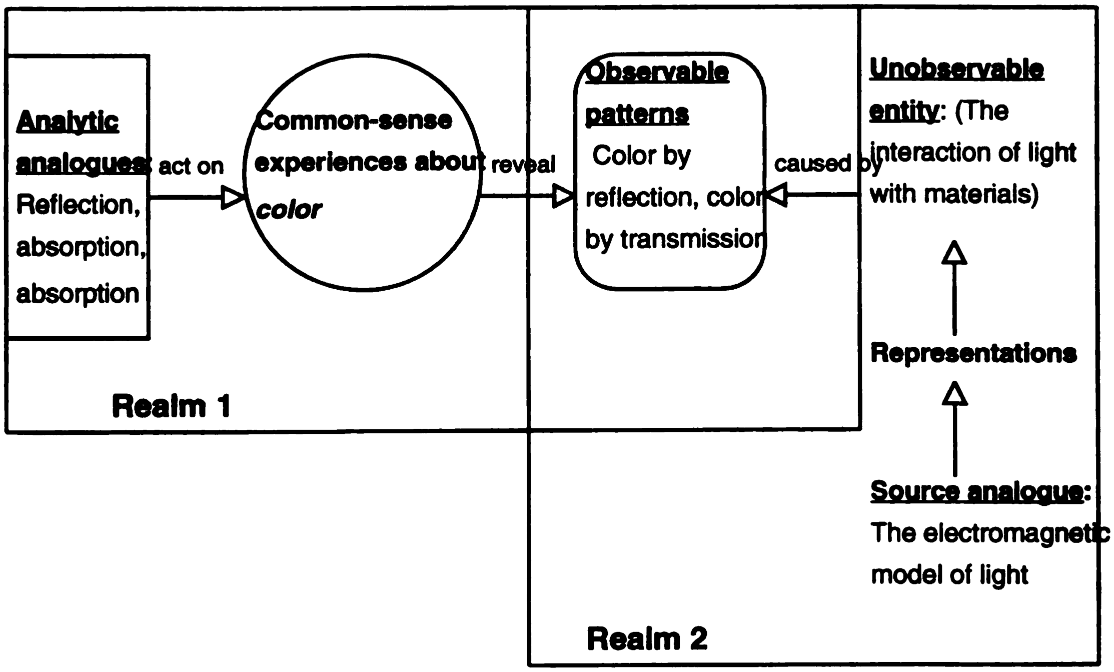

Figure 5.1 : How "reflection," "absorption," and "transmission" in teaching color at the high school level differ from those in teaching optics for prospective physicists or scientists

I used Figure 5.1 to summarize how "reflection," "transmission," and "absorption" in teaching *color* for high school students differ from those in teaching optics for prospective physicists or scientists. In teaching *color* for high school students, "reflection," "transmission," and "absorption" act as three analytic schemes in Realm 1 discourse which enable explanation of a wide range of common-sense experiences about *color*. In teaching optics for prospective physicists and scientists, on the other hand, "reflection," "absorption," and "transmission" are three optical concepts embodied in Realm 2 discourse about the interaction of light with materials. Teaching these concepts emphasizes representing the interaction of light with materials which causes reflection, absorption, and transmission on the basis of the electromagnetic model of light.

2. *The speed of light*

While *the speed of light* is an essential concept for prospective physicists or scientists, it is merely treated as a physical constant ($C=3 \times 10^8$) in teaching optics at the college level. "How fast light can travel" and "how the speed of light was measured historically"--which are the two key ideas in teaching *the speed of light* at the high school level--are seldom discussed in teaching optics for prospective physicists or scientists. Klein & Furtak's *Optics* provides no information about the measurement of the speed of light. Hecht & Zajac's *Optics* presents this piece of information in the first chapter "A brief history". My interviews with the two optics professors support that *the speed of light* is not a topic formally discussed in college optics, and that they never taught about "how the speed of light was measured historically" in their college optics courses (for the interviews, see Chapter 6). Therefore, *the speed of light* is a topic which I am unable to make further comparison of the key ideas for high school students and the key ideas for prospective physicists or scientists.

3. *Light interference*

The last topic *light interference* allows me to make a thorough and integrated comparison of the key ideas for high school students and the key ideas for prospective physicists or scientists. Whether teaching *light interference* for high school students or for prospective physicists or scientists, "constructive interference," "destructive interference," and "coherence" are the three key ideas.

In teaching optics for prospective physicists or scientists, *light interference* can be defined as an interaction of two or more light waves yielding a resultant irradiance[3] which deviates from the sum of the component irradiances (see Hecht & Zajac, 1979; Klein & Furtak, 1986). It can be represented as

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[3] Irradiance is the time rate of flow of radiant energy density.

$$I = I_1 + I_2 + 2\sqrt{(I_1 I_2 \cos\delta)}$$

where I, I_1, and I_2 represent the total irradiance, the irradiance of the first component, and the irradiance of the second component respectively; and $2\sqrt{(I_1 I_2 \cos\delta)}$ represents the resultant irradiance.

"Resultant irradiance" $2\sqrt{(I_1 I_2 \cos\delta)}$ is a key concept in teaching *light interference* for prospective physicists or scientists. It denotes the ideas "constructive interference" and "destructive interference." At various points in the region of interference, the resultant irradiance I can be greater, less than, or equal to $I_1 + I_2$ depending on the value of $2\sqrt{(I_1 I_2 \cos\delta)}$. When $0 < \cos\delta < 1$, we have the result of constructive interference, $I > I_1 + I_2$. When $0 > \cos\delta > -1$, we have the result of destructive interference, $I < I_1 + I_2$ (cf. Hecht & Zajac, 1979).

Another key idea is "coherence." It refers to the condition for light interference. If the interference pattern is to be observable, the phase difference between the two sources must remain constant in time (cf. Klein & Furtak, 1986; Hecht & Zajac 1979).

"Constructive interference," "destructive interference," and "coherence" are the three key ideas in teaching *light interference* for prospective physicists or scientists. This is consistent with the two optics professors' comments about the key ideas in *light interference*. As professor A stated,

> If we are going to have interference, that means we had to be combining waves, and the waves have to be coherent, to be able to interfere. And then you look at the optical path, in order to see whether the interference, is constructive, destructive, or somewhere in between. (IT-PA, 5/22/96)

Professor B thought that "superposition" and "coherence" were the key ideas:

> I think the notion of superposition of beams, and the...tracking if you will, or the appreciation of the importance of the phase difference....When you superimpose two beams, you got to look at the phases....Obviously if you have a phase factor which is rapidly and randomly varied, then I didn't get any interference pattern. Okay. Alternatively if light isn't monochromatic, you are not going to see much interference in effect....By the same token, if, if the spacial coherence is...not presented, if you got two run out of spacial, the path link difference is too great, you are not going to see interference. (IT-PB, 9/18/96).

It is important to point out that "constructive interference" and "destructive interference" are derived from the superposition of two lights when they are in coherence. In this sense, what professor B believed about the key ideas in *light interference* are agreeable with the above three key ideas.

Finally, the two *Optics* texts (i.e., Hecht & Zajac, 1979; Klein & Furtak, 1986) and the two professors indicated that both Thomas Young's experiment and some laser demonstrations provided empirical evidences for *light interference*.

Since teaching *light interference* for high school students and for prospective physicists or scientists involves the same set of key ideas, for the purpose of comparison, I uses Table 5.1 to display the key ideas at the high school level and in the discipline.

Table 5.1 - The key ideas in teaching light interference for high school students and in the discipline

	High School Level	Discipline
Constructive interference	When the crest of one wave overlaps the crest of another, their individual effects add together.	When $0 < \cos\delta < 1$, $I > I_1 + I_2$.
Destructive Interference	When the crest of one wave overlaps with the trough of another, their individual effects are reduced.	When $0 > \cos\delta > -1$, $I < I_1 + I_2$.
Coherence	The two light waves are the same wavelength or frequency, and were in step.	The phase difference between the two sources remain constant in time.
Source analogue	Water waves interference	The electromagnetic model of light
Empirical evidence	Young's experiment or laser demonstration	Young's experiment or laser demonstration

I would like to point out that whatever in teaching *light interference* for high school students or in teaching *light interference* for prospective physicists or scientists, "constructive interference," "destructive interference," and "coherence" belong to type 2 ideas. They all represent the unobservable mechanism (i.e., the interaction of light waves) caused observable patterns of light interference. However, there is an obvious difference. At the high school level, the key ideas are represented through common-sense language involving simple vocabularies, such as "crest," "trough," and "step." In the discipline, the key ideas are represented through the language of mathematics containing technical vocabularies, such as "irradiance" and "phase difference."

Underlying the above difference are the two fundamentally different source analogues used in teaching *light interference* for high school students and for prospective physicists or scientists. At the high school level, the source analogue for building representations for the interaction of light waves is the model of water waves interference (or sound waves interference). In this model, light waves are viewed to be analogous to water waves or sound waves, and the interaction of two light waves to the interaction of two water waves or sound waves. The source analogue used in the discipline, on the other hand, is the electromagnetic model of light. In this model, light is viewed as a classical electromagnetic wave which obeys Maxwell's equations, and the interaction of light waves is seen as the interaction of electromagnetic waves.

In short, the type 2 ideas about *light interference* in the discipline are formulated through the electromagnetic model of light, and are represented through mathematical language. The type 2 ideas about *light interference* at the high school level, on the contrary, are formulated through the model of water waves interference (or sound waves interference), and are represented through common-sense language.

Chapter 6

WHY THE KEY IDEAS IN TEACHING COLOR, THE SPEED OF LIGHT, AND LIGHT INTERFERENCE DIFFER FROM THOSE IN THE DISCIPLINE OF PHYSICS

I first summarize the findings about the differences between key ideas in teaching *color, the speed of light*, and *light interference* for high school students and the corresponding key ideas in teaching optics for prospective physicists or scientists.

Color is an important topic for high school students and yet a negligible topic for prospective physicists or scientists. "Reflection," "absorption," and "transmission" are three essential concepts in teaching *color* for high school students as well as in teaching "the interaction of light with materials" for prospective physicists or scientists. However, while teaching *color* for high school students emphasizes portraying these three concepts at the type 1 level--that is, using the three concepts to explain a variety of phenomena about *color*, teaching "the interaction of light with materials" for prospective physicists or scientists concentrates on discussing the three concepts at the type 2 level--that is, building representations for the unobservable mechanism caused reflection, absorption, and transmission in terms of establishing boundary conditions and solving Maxwell's equations.

The Speed of light is also an important topic in teaching optics for high school students but a negligible scientists. Teaching the topic for high school students involves two key ideas: "how fast light can travel" and "how the speed of light was measured historically". Teaching *the speed of light* for prospective physicists or scientists, however, involves only the physical constant 3×10^8 m/s.

Light interference is an important topic in teaching optics for high school students and for prospective physicists or scientists. "Constructive interference," "destructive interference," and "coherence" are the three key ideas. However, the three key ideas at the high school level are formulated through "water waves interference" (or "sound waves interference"), and the three key ideas in the discipline are formulated through the electromagnetic model of light in form of Maxwell's equations.

The question this chapter addresses is, **why do the key ideas in teaching the three topics for high school students differ from the key ideas in the discipline?** Proposition one & two from my conceptual framework provide primary theoretical perspectives for this question:

1. Given a physics topic, key ideas in teaching school physics represent the psychological structure of subject matter---that are, the structure that follows the historic development of the subject matter, and that is within the experiential world of learners. Key ideas in the intellectual discipline of physics, on the other hand, stand for the logical structure of subject matter--that are, the

structure that is characterized by a body of finished achievements.

2. Within a cultural context, purposes of teaching, knowledge background of learners, and textbooks, each in varying degree, determine what the key ideas are and how the key ideas are formulated in teaching school physics and in the discipline of physics.

In addition, proposition 3 & 4--which are about different theory-types of scientific discourses and the ways of theorizing in Realm 1 and 2 discourses--also provide important perspectives for addressing this question (see chapter two for these two propositions).

This chapter seeks to elucidate how the key ideas in teaching *color*, *the speed of light*, and *light interference* at the high school level stand for the psychological structures of subject matter as compared to the key ideas in the discipline which stand for the logical structures of subject matter. With reference to different theory-types and ways of theorizing, I first contrast the influences of purposes of teaching and knowledge background of learners on what the key ideas and/or how the key ideas are formulated in teaching the three topics for prospective scientists and for high school students; next I examine the ways of selecting and formulating the key ideas for the three topics in the high school textbooks from a historical perspective, with a contrast to the ways in the college texts.[1]

Explaining the difference: Trajectories and purposes of teaching

The trajectory of college optics courses which I studied was typically toward future physicists or scientists. Professor A told me what he taught was a junior and senior level optics course "typically taken by physicists, by astronomers, by engineers, often by mathematicians, and occasionally a few others." Professor B said that his course "was designed for juniors and seniors," and that "almost a half of them are non-physics major; they are electrical engineers, mathematicians, chemists." The purposes of teaching were highly driven by the content of optics, and were centered upon teaching Realm 2 discourse embodied in optical concepts and principles.

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[1] While examining the influence of cultural context on beliefs about purposes of teaching, knowledge background of learners, and ways of constructing textbooks is beyond the scope of this study, I was aware of this influence. Teaching college sciences and teaching school sciences exist within two distinct cultures. The teaching of college sciences aims at the supply of scientific personnel, is more centered upon content or textbooks, and is more characterized by the use of highly specialized language (i.e., theoretical models and mathematics) (Tobias, 1990; C. P. Snow, 1959). On the other hand, teaching school science is more oriented toward the making of work-forces or citizens in the society, is more centered upon the needs and interests of learners, and is more characterized by the use of non-sophisticated language (AAAS, 1989; Deboer, 1991). These striking differences in the norms of science teaching inherent in two different cultures find some echoes from my interviews with the two optics professors and the two high school physics teachers.

For professor A, the purposes of teaching involved teaching the content of optics and illustrating the observable effects of optical concepts or principles:

> I say at least the way I teach it at the college level. There are two unseparated purposes. One purpose is to just straightforwardly teach the content of optics, and particularly in physical optics, I also use it as an example of more abstract concepts, which then in fact can be seen realistically, and make more understandable. (IT-PA, 5/22/1996)

For professor B, teaching the curriculum and elucidating the visible aspects of optical concepts or principles were the purposes of teaching:

> I can give you the easiest answer, and say, well it is in the curriculum, somebody asks to.... Personally, I, I think that, ah, optics, is a nice vehicle, for, ah, elucidating, the principles of electricity and magnetism, in a very visual way. (IT-PB, 9/18/1996)

To illustrate the observable effects of optical concepts or principles (i.e., the distinct feature of Realm 2 discourse embodied in optical concepts or principles), professor A contrasted *optical interference*--which could be seen realistically--with *quantum mechanical interference*--which couldn't be seen realistically:

> An example would be that in physical optics, we can talk about coherence, which then leads to interference. On the other hand, in quantum mechanics, you often talk about wave functions, and you talk about the kind of interference that can happen quantum mechanically, that is a very big abstract concept, but rely upon all the same principles and many of the same mathematical operations as optical interference does. You can talk about optical interference and then go to the lab, and you can see it practically and immediately. So that makes the quantum concept

less mysterious. (5/22/1996)

Professor B also contrasted *optical interference*--which people could "fix mentally, more precisely, what is happening" through experiments--with *quantum mechanical interference*--which was "some sort of mathematical fantasy":

> I have a real belief that for many people, including myself, things don't become real until you can see them with your eyes....you can visualize it and then you can see it. It takes on a reality which is unshakable. And, and yes I can talk about quantum mechanics, and I can talk about interference as gathering events....But it is just math. Okey, you can go to the computer, you can have it do the calculation, even you can have it do a graph. That is not the same. That is not the same, at least for me. I can, you know, I can, I can look at an [optical] interference pattern... [thus] make the process real. And, and as a result of that, it enables me to sort of fix mentally, more precisely, what is happening....I set up this demonstration and actually have the students look through this telescope, and look at this interference pattern.... My purpose...is to really get them to believe that interference happens. That it really occurs. That is not some sort of mathematical fantasy that we can talk about. You can see the effect just as you can see it in a ripple tank. It, is, the optical analogue of a ripple tank. (IT-PB, 9/18/1996).

On the contrary, the trajectory of the two high school physics courses I studied was not toward future physicists or scientists. For the two high school physics teachers, high school physics was probably the last physics course for many high school students. Mr. Barnes said,

> See a lot of these students may never take college physics. So I like them to get into appreciation for the world around us. A lot of them are not going to take college physics. Most of them are not going to even major in physics. I may have one or two out of my two classes who might major in physics. OK! so I want them to understand the

> concepts, I want them to have an appreciation for the world around them, and how things work and how things interrelated. (IT-Barnes, 4/18/1996)

Mr. Kennedy indicated that "I am not fooling myself they are going to remember a lot of physics, or they are going to become physicists."

In consonance with such a trajectory, the purposes of teaching were centered upon the needs of high school students and were driven by Realm 1 discourse. Having students understand basic concepts and principles and having students explain and interpret the physical world were two essential purposes in their teaching. Mr. Barnes stated,

> I want them to understand basic concepts, I want them to have an appreciation for the world around us, and how things work and how things are interrelated... I want them to understand the world around us, and to be able to interpret in terms of physics (IT-Barnes, 4/18/1996)

Mr. Kennedy said,

> I just want them to have basically another year of problem solving, another year of understanding the fundamentals, and another year of looking at the world, interpreting the world, and be ready for the next science class. (IT-Kennedy, 5/8/1996)

To summarize, each trajectory is associated with distinctive purposes of teaching. On the trajectory toward future physicists or scientists, the purposes of teaching are driven by the content of optics; teaching Realm 2 discourse is a distinct purpose of teaching; on the trajectory of preparing high school graduates, the purposes of teaching are more centered upon the interests and needs of students; teaching Realm 1 discourse in terms of explaining and interpreting the natural world is an unique purpose of teaching.

These differences in purposes of teaching can explain why the key ideas in teaching *color* and *the speed of light* for high school students differ from those in the discipline of physics.

1. *Color*

The topic *color* is important in teaching optics for high school students because "color" is part of the physical world which they experience. As Mr. Barnes explained,

> Well, you can't talk about light without talking about color. Colors are all around us, you can see examples everyday. Why is it...a sweater...why is it red? You also see examples where different color objects are under different colors of light in appearance of different colors. Here is a red sweater under a blue light. They see thing like this... And the kids like it. Colors are all around us, you can see examples everyday....(IT-Barnes, 4/21/96)

Mr. Kennedy said,

> Color is a big part of their world. It is interesting. They enjoy it. We try to point out, you know, how physics brought this up, everyday...(IT-Kennedy, 5/8/96)

Implicitly, teaching type 1 ideas about *color* serves the purpose of having students explain and interpret the physical world.

However, type 1 ideas about *color* don't have a legitimate place in teaching optics for prospective scientists. These ideas fail to serve the purpose of representing Realm 2 entities in form of theoretical models and mathematical language. In the comment on the insignificance of the topic *color* in the discipline, professor A pointed to the lack of mathematical language and of connectedness with other physics concepts or principles:

> Color is not that important at the college level, because it is really, too simple idea...simple in a sense that the mathematics required to understand what is going on is absolutely minimum, or almost non-existent. And secondly it is the kind of thing, Ah, you can read very quickly to understand... It is also not an idea that builds upon anything and leads to somewhere else. It's just sort of effect that occurs, and explains how you perceive things in the real world. But it doesn't mean any thing beyond that. (IT-PA, 8/28/1996)

Professor B believed that the topic *color* might satisfy the curiosity of some people, but the ideas about *color* were "sort of barren" and lacked of "any transcendent importance":

> I think my sense is that, that while, color, may be important, sort of in a general context, to satisfy people curiosity, as to why something is brown or something is blue, and so on....But it strikes me it is sort of barren, ah, set of ideas....I don't see it has any transcendent importance... So, I think at the student level, people are curious of how color is duplicated and to the extend we think we understand that, is, is sort of issue which has no future. (IT-PB, 9/18/1996)

Therefore, for the purpose of having students explain and interpret the natural world, type 1 ideas about *color* in form of descriptive language are essential in teaching optics at the high school level. However, for the purpose of teaching Realm 2 discourse in form of mathematical language, these ideas don't occupy a legitimate place in teaching optics for prospective physicists or scientists.

2. *The speed of light*

"How fast light can travel" and "how the speed of light was measured historically" are two type 1 ideas about *the speed of light* in form of descriptive language. They are important in teaching optics for high school students because they are centered upon the interests and needs of high school students. Mr. Barnes believed that high school students were interested in knowing about "how fast light can travel" and "how the speed of light was be measured":

> Well, as soon as you tell them, how, you know the speed of light 186,000 miles/sec. They know it is a big number. But they don't know how big it is. And the next question is, how someone ever figured that out? How they measured it. They used the stop watch, they used the stop watch, and turn off and on switch. No! That is what we did in mechanics with cart, you have a cart going down a table, add a photo gate timer, and we have a stop watch, we start it hear and stop it here....Yes, for sound, maybe, why can't we do it for light. It goes away too fast. Wow, how do we know it go on 186,000 mile/sec? Well, there were some men that did some experiments that tried to find out. So let's look at, I add a little bit of history. So the velocity, just at the standpoint of interesting. How far does light go and how do we know. So kids, I found over the years would ask these questions. How do we know that fast?. That is really fast.... Kids may come up with that. How do we know that fast? So, from now on, I just, I just present these to students. They didn't asked about Reomer's result, but over the years they asked me, how do we know light goes that fast? Who measured it? How do we know? Did someone just made it up? What kind of instrument did they use? Anything right on the lab here... So, they want to know. That is a very special velocity, very special.

(IT-Barnes, 4/18/1996)

Mr. Kennedy thought that high school students needed to know about "how fast light can travel":

> For many high school students, this [high school physics] would be the last exposure to physics. They would not take physics in colleges. OK. I just think that light, and even thought we didn't go into or mention that it is the foundation of relativity. Ah, it is the fastest that we can transfer information. Ah, and even though I go very fast I try to give them a sense of the universe so large that...I just try to convey them some of the beauty...Ah, light is the same speed as radio waves and others, Ah, radar, X-rays, things they might talk about...but really know what they are...(IT-Kennedy, 5/8/1996)

In other words, teaching "how fast light can travel" and "how the speed of light was measured historically" reflect the purposes of teaching concepts and principles that are centered upon the interests and needs of students.

On the contrary, "how fast light can travel" and "how the speed of light was measured historically" are not the key ideas in teaching optics for prospective physicists or scientists, because they are not the important issues in the content of college optics. For the "how fast light can travel," professor A indicated that "the speed of light" was a given number in the content of optics, while it was a key idea in other branches of physics (e.g., mechanics and relativity):

> When you get to college optics. That [the speed of light] is already assumed....That is the foundation you already assume there....In optics we wouldn't spend much time talking about the speed of light because it is a fundamental value we assume that they understand. On the other hand,

> when we talk about mechanics, when we talk about relativity, we spend a lot of time on talking about the speed of light. (IT-PA, 8/28/1996)

Professors B also suggested that "the speed of light" was treated as a key idea in other areas of physics (e.g., electricity and magnetism)[2] but not in the area of optics:

> Ah, I said it is important, but it is not something we do in optics, because they [students] should have seen it some place else.... It is not something that particularly dwell upon a optics course. And the reason for that is , that, that it is something that we typically emphasize in E & M [electricity and magnetism]. (IT-PB, 9/18/1996)

For "how the speed of light was measured historically," both professor A and B suggested that it was unnecessary for students to know about it because they could provide students an experiment to measure the speed of light with modern methods:

> They won't be so, so interested necessarily in the history....Ah, we can tell them how we do it modernly. Ah, and in fact, in one of our advanced labs, we actually set up a situation. And the students attempt to measure the speed of light. And they discover, limited distance, such as distance in the hallways in this building....And you see really good, the way you actually measure it in a modern sense....(IT-PA, 8/28/1996)

> We have a advanced laboratory experiment they can do if they want to measure the speed of light. Ah, and, and if they are interested in the subject, they can do it in the lab....(IT-PB, 9/18/1996)

Taken together, "how fast light can travel" and "how

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[2] The speed of light is one of the most important fundamental physical constants. In mechanics (particularly in astronomy), it is used to convert light travel times to distance to Moon and planets. In relativity, it relates mass m to energy E in Einstein's equation, $E=mc^2$.

the speed of light was measured historically" are not the key ideas in teaching optics for prospective physicists or scientists because these two ideas are apart from the content of college optics. In other word, teaching these two ideas is irrelevant to the purposes of teaching which are typically driven by the content.

The above differences between the key ideas in teaching *color* and *the speed of light* at the high school level and the key ideas in the discipline of physics indeed manifest the distinction between the psychological structure and the logical structure of subject matter. The key ideas in teaching at the high school level represent the psychological structure of subject matter because they are built upon the experiential world of high school students characterized in terms of Realm 1, the Realm of actual objects or common-sense experience. The key ideas in the discipline, on the other hand, stand for the logical structure of the subject matter because they are built upon Realm 2--the realm of possible objects of experience in form of theoretical models and mathematical equations--or are characterized in form of achieved outcomes of scientists' understanding.

Explaining the differences: Knowledge background of learners

Knowledge background of learners imposes a constraint on what ideas can be taught and how ideas should be formulated in teaching a given topic to learners at certain stages. Also, it is a referent for proper ways of formulating ideas to the learners. Contrasting this factor in teaching *light interference* for prospective physicists or scientists and for high school students can explain why the source analogue for prospective physicists or scientists is the electromagnetic model of light and the one for high school students is "water waves interference" (or "sound waves interference").

In the interviews, professor A & B highlighted advanced mathematics and electromagnetism as the prerequisites for learning optics based upon the electromagnetic model of light. Professor A articulated the requirement for students' knowledge background and experience as follows:

> They need to have familiarity with expressing waves mathematically. They need to be able to deal with complex numbers and representations of complex numbers....Oh, and it certainly helpful but not absolutely essential that they need to be able to do basic integration....In order to really learn physical optics, they had to have a solid background in electromagnetism....On the other hand, in order to simply use reliably and consistently a lot of the topics in physical optics, they really had to understand electricity and magnetism mathematically. (IT-PA, 5/18/1996)

While professor B also stressed advanced mathematics, electricity and magnetism (electromagnetism) as the requirement, he included introductory physics and modern physics as well:

> Okay, the formal requirement, ah, beside the advanced math requirement, we require them to have had the introductory sequence in physics, which is mechanics, and then E & M [electricity and magnetism]. And then also to have modern physics courses. So we expect basically them to have at least three semesters of physics, up through modern physics before they take optics. (IT-PB, 9/18/1996)

Obviously, it is really difficult (if not impossible) to formulate the key ideas about *light interference* for high school students through the electromagnetic model of light due to their knowledge background. I asked each teacher why he could not teach "constructive interference," "destructive interference," and "coherence" by using Maxwell's equations. The response provided by each of them highlighted the constraint imposed by the knowledge background of high school students. Mr. Barnes stated,

> They know very little about magnetism. We haven't started magnetism yet. They don't know anything about electricity. So if all of sudden I drop that in here. They don't have any knowledge, if I say electromagnetic waves and let's go about electromagnetic theory. They don't know....A lot of the kids in high school haven't had the mathematics background, only a few of them are in calculus. A lot of them are just in trigonometry ....So if you start putting up a complicated equation, they are going to get lost. (IT-Barnes, 4/18/1996)

Mr. Kennedy said,

> Even most college texts say you can't have an appreciation of Maxwell's equations unless you have at least three years of calculus. And for my students they don't have three years of calculus, very small percent are taking calculus right now. Oh, it is beautiful, and I hope that these people that go to college are exposed to these, but I just think that it is a little too abstract for the average high school students....They are not

> ready, mathematically, Oh, everything you do with Maxwell's equations with math, you can't teach them at high school level. (IT-Kennedy, 5/8/1996)

In short, the knowledge background of high school students determines that the electromagnetic model of light cannot be employed in the formulation of the type 2 ideas about *light interference*.

Accordingly, it is of necessity of taking the knowledge background of learners into account in determining the appropriate source analogue in formulating and representing type 2 ideas. The source analogue should be derived from what high school students already know or are familiar with. In building representations for the type 2 ideas about *light interference*, the two teachers began with the discussion of water waves and sound waves, and then moved toward the discussion of light waves. By following such a sequence, they used "water waves interference" (or "sound waves interference")--a model in Realm 1 discourse--as the source analogue. Mr. Kennedy regarded this sequence as "a logical and natural sequence" for it follows the progression from knowing to unknowing, from "concrete" to "abstract":

> Because you start with what they are more familiar with, what they have more experience with, what they have more hands-on with. And then you go to something which is little more abstract, superposition they hadn't exposed to that before but the examples we used, they did a pretty good job with it. And then I think as you go on, each of these is a little more complex, built upon the earlier one. To me, that is a logical and natural sequence. Ah...be very difficult you can't teach interference without superposition first, because interference depends upon superposition. (IT-

Kennedy, 5/8/1996)

Mr. Barnes emphasized the use of some common properties of waves--which were derived from the discussions of mechanical waves, water waves, or sound waves--to make the ideas concrete and tangible to students:

> What is wave? How do waves behave? I use some properties of waves to help them understand, something they can see without getting too extremely theoretical and mathematical. They need more concrete examples, and more tangible examples that they can see and they can work with...(IT-Barnes, 4/18/1996)

While "water waves interference" (or "sound waves interference)" is a meaningful source analogue in teaching *light interference* in light of the knowledge background of high school students, it is an inappropriate source analogues for prospective physicists or scientists. Professor didn't think it is necessary to follow the above sequence (from "waters waves" or "sound waves" to "light waves") due to kind of knowledge background of learners (prospective physicists and scientists). He stated,

> No, I don't think it is necessary...for instance at the college level, they are more comfortable with the math. They are able to do a lot more things by just doing the math and seeing the consequence of it. (IT-PA, 8/28/1996)

Professor B also believed that it is not necessary to follow the sequence in teaching *light interference*:

> It is not clear to me that you couldn't appreciate interference in light without ever having seen a ripple tank. I don't think there is anything magical about ripple tank, in term of giving you an appreciation for the interference of light. In fact in some aspect, I think you can equally well

> teach interference of light without ever having used the ripple tank. (IT-PB, 9/18/1996)

Furthermore, he believed that the above progression didn't necessarily lead to a proper formulation of optical interference:

> But that is what I say if you follow this progression, you are unnecessarily leading up to optics, from my perspective. What you are doing, is demonstrating to the students how universal interference among waves it is. And that include material waves, pressure waves, light waves. I mean that, that progression may play upon the, ah, background of high school students. But in doing so, I don't think it's necessarily leading up to light waves interference as the pinnacle of these. All you are doing then is using light waves as yet another example of superposition and interference. (IT-PB, 9/18/1996)

To summarize, because of the constraint imposed by the knowledge background of high school students, it is impossible to use the electromagnetic model of light as the source analogue in formulating the ideas about *light interference*. The source analogue ("water waves interference" or "sound waves interference") used in teaching the ideas is appropriate for students in light of their knowledge background, and yet inappropriate for prospective physicists or scientists in light of the theoretical model used in the discipline of physics (for a discussion about the inappropriateness, see chapter seven).

The above difference between the key ideas in teaching *light interference* at the high school level and the key ideas in the discipline clearly reflects the distinction between the psychological structure and the logical structure of subject matter. The key ideas at the high school level stand for the psychological structure of subject matter because they are formulated through the source analogue which belongs in Realm 1, and is relevant to the knowledge background of high school students. The key ideas in the discipline, on the other hand, stand for the logical structure because they are formulated through the source analogue which belongs in Realm 2 formed by the electromagnetic model in form of Maxwell's equations.

Explaining the differences: the way of selecting and formulating key ideas in textbooks

Now I examine the way of selecting and formulating the key ideas for *color, the speed of light*, and *light interference* in the high school texts from a historical perspective, with a contrast to the way in the discipline.[3] I will argue that the key ideas in the high school texts stand for the psychological structures of subject matter because they are selected and formulated in a fashion that

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[3] I examine the textbooks for two reasons. First, as already indicated in chapter two, textbooks are the resources for key ideas in teaching physics for high school students. Second, there is a high consistency between the key ideas taught by the two teachers and the key ideas in the two high school texts. In other words, the claim generated from examining the key ideas in the two textbooks can be generalized to the key ideas in teaching.

is consistent with the historical process of developing the subject matter. The key ideas in the discipline of physics, on the other hand, represent the logical structures of subject matter because they highlight the achieved outcomes but ignore the historical process of developing the subject matter.

1. *Color*

In chapter four I already showed that the key ideas about *color* in the two high school texts involve "transparent," translucent, and opaque," "the combination of white light," "color mixing by substraction," and "color mixing by addition" at the type 1 level. And the presentation of these ideas starts with a recapitulation of Newton's famous investigation of the combination of white light. A brief survey of the early history of optics reveals that these key ideas capture some important epochs in the development of scientists' understanding about the nature of light.

Isaac Newton was the first person to study *color* systematically. In 1666, he allowed a beam of white light to pass through a prism, and he found a spectrum of seven colors. Newton thus concluded that white light is composed of a mixture of a whole range of seven different colors. By this view of light, scientists in the seventeenth century were able to explain why an object could be transparent or opaque, and how colors could be formed. An objects can be transparent if it transmits all colors of light, or opaque if it absorbs all colors of light. Some substances may absorb some colors and transmit others. Colors thus can be formed by transmission or reflection. Eventually, scientists formed the ideas of "transparent and opaque," "color by reflection," "color by transmission," and "color mixing by subtraction".

"Color mixing by addition" was also an important idea in the history of optics. In 1807, Thomas Young, who had been a very influential figure in the development of physical optics, pointed out that red, green and blue could, in proper combination, give rise to the sensation of any other color. This was later further developed by the German scientist Hermann Ludwig Ferdnand von Helmholtz. It is therefore called the Young-Helmholtz theory of color vision (see Asimov, 1985 or Cajori, 1962, for a complete history of *color*).

Evidently, in the high school texts the key ideas about *color* at the type 1 level are also the "key ideas" in the early stage of optics. They are formulated in consistence with the historical process through which scientists developed their understanding about *color*. Hence the key ideas about *color* in the high school texts stand for the psychological structure of subject matter. However, the type 1 ideas about *color* no longer exist in the college optics texts which mainly record the type 2 ideas about the interaction of light with materials formulated through the electromagnetic model of light and mathematical language (see chapter five, for a detailed discussion). Key ideas in the college textbooks, thus, stand for the logical structure of subject matter.

2. *The speed of light*

As revealed in chapter five, "how fast light can travel" and "how the speed of light was measured historically" are the two key ideas for *the speed of light* in the two high school texts. These two ideas are elucidated through a recapitulation of the measurement of the speed of light done by Galileo, Roemer, Fizeau, and Michelson. Examining the early history of optics reveals that "how fast can light travel?" and "how can the speed of light be measured?" were indeed two critical questions that numerous scientists and astronomers had been grappling with for more than two centuries. Several great scientists, Galileo, Roemer, Bradley, Fizeau, Foucault, and Michelson, made crucial contributions to scientists' progressive understanding about "how fast light can travel" and "how the speed of light was measured".

The first contribution was made by Galileo who showed by his experiment that light traveled faster than sound. The second contribution was made by Danish astronomer Olaus

Roemer. In 1670, Roemer succeeded in showing that light traveled at velocities of the order of a hundred fifty thousand miles a second, through making meticulous observations of Jupiter's satellites. In 1728, English astronomer James Bradley showed that the speed of light was nearly 190,000 miles a second by observing the phenomenon of the aberration of light through a telescope. In 1849, French physicist Louis Fizeau developed an innovative method for measuring the speed of light which involved rotating a cogged wheel and a distant mirror. French physicist Jean Leon Foucault made an improvement on Fizeau's method through introducing a second mirror. In 1850, Foucault found that the speed of light in water was distinctly less than that in air. The most famous and accurate experiment measuring the speed of light was performed by American physicist Albert Michelson. He made use of a refined version of Foucault's set up and method. In 1926, Michelson obtained for it a speed of 299.796 km. per second. As the result, he became the first American physicist to receive the Nobel prize in physics (see Asimov, 1985; Cajori, 1962, for a complete history about *the speed of light*).

Therefore, "how fast light can travel" and "how the speed of light was measured historically" are not only the key ideas in high school texts, but also the "key ideas" in the historical development of scientists' understanding about *the speed of light*. In this sense, these two key ideas render the psychological structure of the subject matter. However, "how fast light can travel" and "how the speed of light was measured historically" are no longer "key ideas" in the college optics texts (see chapter five). The two college optics texts only record the physical constant ($C=3 \times 10^8$) which represent the finished measurement result of the speed of light. In this meaning, the key ideas in college optics texts stand for the logical structure of subject matter.

3. *Light interference*

As indicated in chapter four, the key ideas about *light interference* in the two high school texts are formulated through recapitulating Thomas Young's experiment and employing the source analogue in Realm 1 discourse, "water waves interference" (or "sound waves interference"). A brief survey of history reveals that it is consistent with the progression through which scientists came to grasp the essence of *light interference* in the eighteen century.

In 1690, Christian Huygens proposed the first complete wave theory of light. According to Huygens, light waves spreading out from a point source could be considered as the overlapping of tiny secondary wavelets, and that every point on any wave front could be considered as a new point source of secondary waves. Huygens assumed that the behavior of light waves was very similar to sound waves or water waves.

In 1801, Thomas Young convincingly demonstrated the wave nature of light through his famous two-source interference experiment, through comparing light interference patterns with the interference patterns created by water waves or sound waves. It was only after James Clerk Maxwell successfully developed electromagnetic theory in 1862 that had scientists started to view light as an electromagnetic wave (see Asimov, 1985; Cajori, 1962, for a complete history about *light interference*).

Explicitly, the key ideas about *light interference* in the two high school texts stand for the psychological structure of subject matter because they are formulated in high accord with the historic paths through which scientists developed their understanding about *light interference*. On the contrary, the key ideas in the two college optics texts represent the logical structure of subject matter because they are formulated in a way that highlights the achieved outcome of scientists' understanding--that is, our understanding of *light interference* based upon the electromagnetic model.

Taken together, for *color*, *the speed of light*, and *light interference*, the key ideas in the high school texts--which are selected from and are formulated based upon Realm 1 discourse--stand for the psychological structures because the way of selecting and formulating these ideas is in consonant with the historic process through which scientists developed their understanding. On the contrary, the key ideas in the college texts--which are selected from and are formulated based upon Realm 2 discourse in form of theoretical models and mathematical equations--mirror the logical structures of the subject matter because the selection and formulation of the key ideas highlight the "finished" outcomes but ignore the historic process through the outcomes were developed.[4] In other words, the key ideas about *color*, *the speed of light*, and *light interference* in the high school texts are identified from the "key ideas" in the historical development of the subject matter, rather from the "key ideas" in the intellectual discipline; and the way of formulating these key ideas follows the historical routes rather than the logical paths in the discipline of physics.

It is worth noticing the psychological and epistmological significance of this way of selecting and formulating key ideas in high school texts. For one thing, it is in high accord with Dewey's idea about psychologizing subject matter. Psychologizing subject matter involves a restoration of scholarly subject matter into the experience from which the scholarly subject matter is abstracted. By following the historical paths, the key ideas in high school texts can capture the kind of difficulties, wonders, or

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[4] Kuhn (1970) also argued that college science textbooks record finished scientific achievements but omit the historical processes of developing the achievements.

progresses that scientists had to go through in developing their understanding of the subject matter.[5]

For another, historical selection and formulation of key ideas in a school science curriculum reflect the progression and ontological continuity in the development of scientific discourse. By following the historical paths, high school texts bring Realm 1 discourse to the forefront. High school texts thus can build on and extend students' experiences and knowledge of macroscopic phenomena, and eventually move toward the understanding of some entities in Realm 2 or 3 discourse.

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[5]The psychological significance of historical presentation of subject matter also gains influential voice in Piaget's "genetic epistemology" and Hogg's "historic development" in construction of a science curriculum. Piaget (1974) believed that "learning of structures seems to obey the natural development of these structures." (p. 184). This belief is based upon his genetic epistemology. Piaget said,

> The fundamental hypothesis of Genetic Epistemology is that there is a parallelism between the progress made in logical and rational organization of knowledge and the corresponding formative psychological processes. (Piaget, 1970, p. 13)

Chemist Hogg noticed the principle of parallelism implied in Piaget's theory. He proposed a historical approach in the development of a science curriculum:

> The historic development is a logical approach. The slow progress of the early centuries was owing to a lack of knowledge, to poor technique and to unmethodical attack. But these are precisely the difficulties of the beginner in the chemistry. There is a bound of sympathy between the beginner and the pioneer. (Hogg, 1938. p. vii)

CHAPTER 7

OVERVIEW, CONCLUSIONS, AND IMPLICATIONS

This final chapter is divided into three main parts. The first part provides an overview of the study including research questions, conceptual framework, methods, and findings. The second part presents the conclusions of this study through discussing three claims. The third part addresses the implications of this study for science teacher education, research on science teachers' pedagogical content knowledge, and construction of a science curriculum.

Overview

This study aimed to clarify the distinction between key ideas in teaching school physics and key ideas in the intellectual discipline of physics. By key ideas in teaching school physics, I mean the concepts or principles that are essential for students of a particular age to understand a particular physics topic. I define key ideas in the discipline of physics as the concepts or principles that are essential for scientists or physicists to understand that topic. This distinction between key ideas in teaching school science and key ideas in the intellectual disciplines of science is crucial and yet largely ignored in scholarly discourse about what science teachers should teach and what science teachers should know.

This study was guided by two questions:

1. How do key ideas in teaching school physics differ from those in the discipline of physics?

2. Why do key ideas in teaching school physics differ from those in the discipline of physics?

The conceptual framework of this study was developed based upon Dewey's idea of *psychologizing subject matter* and Harre's theory of *referential realism*. It consists of four propositions:

1. Given a topic in physics, key ideas in teaching represent the psychological structure of the subject matter--that is, the structure that follows the historic development of scientists' understanding of that topic, and that is centered around the experiential world of learners. Key ideas in the intellectual discipline of physics, on the other hand, stand for the logical structure of the subject matter--that is, the structure that is constituted by a body of achieved outcomes of scientists' understanding.

2. Within a cultural context, purposes of teaching, knowledge background of learners, and textbooks, each in varying degree, determine what the key ideas are and how these ideas are formulated in teaching physics for school students and in teaching physics for prospective physicists or scientists.

3. Key ideas teaching school physics or in the intellectual discipline of physics can be categorized into three theory-types, the referents of which are relative to

the possibilities of human experience. *Type 1* theories enable constitution, classification, and prediction of observable phenomena. The referent of type 1 theories belong in *Realm 1*, the realm of actual objects of human experience. *Type 2* theories enable the representation of a certain kind of unobservable entities which can only be made available to human perceptions through experimentation. The referent of type 2 theories belong in *Realm 2*, the realm of objects of possible experience. *Type 3* theories enable the representation of the kind of entities which cannot be observed. The referents of type 3 theories belong in *Realm 3*, the realm of objects beyond all possible experience.

4. The development of realm 1 discourse (or type 1 theories) involves the use of analytical analogues, and the development of realm 2 discourse (or type 2 theories) involves the use of source analogues. Realm 1 discourse is grounded in the physical world. Realm 2 discourse is developed based upon realm 1 discourse and scientific experiments.

This study is composed of three components: 1) a case study of two experienced physics teachers that examines what the key ideas are and how the key ideas are formulated in teaching three topics, *color*, *the speed of light*, and *light interference*, at the high school level; 2) a comparative analysis of the key ideas in teaching the three topics at the high school level and the key ideas in the discipline of physics; 3) interviews with the two physics teachers and two optics professors concentrating on why the key ideas in teaching at the high school level differ from those in the discipline.

The research findings can be summarized as follows:

Finding 1. The difference between the key ideas in teaching *color* and *the speed of light* at the high school level and the key ideas in the discipline of physics is indicated in theory-types, and is determined by the different purposes of teaching for highs school students and for prospective physicists or scientists. The type 1 ideas about *color* and about *the speed of light* in form of descriptive language serve the purpose of helping high school students understand concepts or principles that are centered around their interests and needs, and the purpose of helping them explain the physical world. However, these ideas are outside the realm of teaching optics for prospective physicists or scientists because helping learners understand type 2 ideas in form of theoretical models and mathematical equations is the essential purpose of teaching at this level.

Finding 2. The difference between the key ideas in teaching *light interference* for high school students and the key ideas for prospective physicists or scientists is evident in the various source analogues used in formulating the topic, and is determined by the different knowledge backgrounds of learners. The source analogue at the high school level is "water waves interference" (or "sound waves interference") that is centered upon the knowledge background and experiential world of high school students. However, the source analogue in the discipline is the electromagnetic model of light that is relevant to the knowledge background of prospective physicists or scientists.

Finding 3. The differences between the key ideas in teaching *color, the speed of light*, and *light interference* for high school students and the corresponding key ideas in teaching optics for prospective physicists or scientists are influenced by the way of selecting and formulating key ideas in textbooks. The key ideas in high school textbooks are selected and formulated in a way that is consistent with the historical processes through which scientists developed their understanding of the topics. On the contrary, the key ideas in textbooks for prospective physicists or scientists are selected and formulated in a fashion that highlights the achieved outcomes of scientists' understanding of these topics.

Conclusions

What the above findings reveal to us, on the forefront, is that key ideas in teaching school physics are markedly different in theory-types, source analogues, and representations from key ideas in the discipline of physics. These differences are indeed manifestations of the distinction between the psychological and logical structures of subject-matter knowledge. The key ideas in teaching the three topics represent the psychological structures of subject-matter knowledge because they are centered upon the experiential world and knowledge background of learners, and they reflect the historical development of subject-matter knowledge. The key ideas in the discipline of physics, on the other hand, stand for the logical structures of subject-matter knowledge because they are achieved outcomes of current scientific understanding in form of theoretical models and mathematical language.

Making a clear distinction between key ideas in teaching school physics and key ideas in the discipline of physics is very crucial to our discourse about what science teachers should teach and what science teachers should know. Now I establish three claims to address the three issues I raised in chapter one, each of which derives from the lack of a distinction between key ideas in teaching school science and key ideas in the discipline of science in scholarly discourse about what science teachers should teach and what science teachers should know:

1) Can any idea in the discipline of physics be taught to anybody of any age?

2) Is knowing the structures of the academic discipline

of physics sufficient for physics teachers to teach school physics?

3) In what sense do key ideas in teaching school physics constitute a component of pedagogical content knowledge?

Claim 1. Not every idea in the discipline of physics can be taught to anybody of any age in a way that is intellectually honest to the discipline.

My first claim is a challenge to Bruner's (1961) proposition that "any subject can be taught effectively in some intellectually honest form to any child at any stage of development" (p. 33). This proposition is based upon a premise that "any idea can be represented honestly and usefully in the thought forms of children of school age" (p. 33). Two warrants justify my claims.

The first warrant is the constraint imposed by the knowledge background of learners at certain levels on the ways of representing or formulating some type 2 scientific ideas in the discipline. As already addressed in chapter 6, it is impossible to represent the type 2 ideas about *light interference* to high school students through using the source analogue in the discipline, the electromagnetic model in the form of Maxwell's equations, because of their lack of knowledge background in electromagnetism and advanced mathematics. In other words, the lack of knowledge background for a certain source analogue used in the discipline of physics determines that some type 2 ideas cannot be represented to the learners through the analogue in the discipline.

Representing the type 2 ideas about *light interference* through "water waves interference" (or "sound waves interference") as the source analogue seems to be relevant to the thought form of students in terms of their knowledge background and experience. This is the approach depicted in the two high school textbooks, and was adopted by the two experienced physics teachers in my study. It was indeed a highly recommendatory approach to the teaching of *light interference* which was said to be consistent nicely with Bruner's premise in the 50s curriculum reform movement.[1]

However, teaching *light interference* through the model of water waves interference (or sound waves interference) is intellectually dishonest to the intellectual discipline of physics. As already indicated in chapter six, "water waves interference" (or "sound waves interference") is an inappropriate source analogue for *light interference* because it doesn't necessarily lead to a proper formation of optical interference. Below I discuss future the inappropriateness of this source analogue in building representations for *light interference*.

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[1] See the two physics textbooks developed in the 50s curriculum reform movement, HPP's (1968) *An introduction to physics* and PSSC's (1960) *Physics*.

The representations of *light interference* based upon the model of water waves interference (or sound waves interference) are fundamentally incompatible with the representations in the intellectual discipline of physics--that are, the representations based upon the electromagnetic model of light. Using "water waves interference" (or "sound waves interference") as the source analogue implies that light is a mechanical wave whose propagation requires a medium and is governed by Newtonian laws. However, the source analogue in the intellectual discipline, the electromagnetic model of light, envisions that light is an electromagnetic wave that can propagate in the absence of a medium and obeys Maxwell's electromagnetic equations. These two representations of *light interference* are fundamentally incompatible in a sense that the representations in the discipline can be accepted only with the recognition that the representations based upon the model of water waves interference or sound waves interference are wrong.[2]

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[2] Over the eighteenth and nineteenth century, scientists widely held that light is a wave motion propagated in a mechanical ether or medium governed by Newton's laws. However, such a Newtonian wave theory of light was rejected completed with the acceptance of Maxwell's electromagnetic theory as the wave theory of light, and particularly with the refutation of the existence of such a mechanical ether or medium by scientific experiments near the end of nineteenth century. The shift from Newtonian wave theory of light to Maxwell's wave theory of light is indeed a scientific revolution. Scientists had to undergone a displacement of the conceptual web through which they viewed the nature and behavior of light (Kuhn, 1970; Asimov, 1984).

The lack of specific knowledge background for the appropriate source analogue for some type 2 ideas in the discipline, thus, determines that these type 2 ideas cannot be represented to high school students in a way that is intellectually honest to the discipline. While Bruner emphasized the "constraint" imposed by a particular stage of intellectual development conceived by Piaget and others on learning certain mathematical ideas, he had neglected the constraint imposed by specific knowledge background of learners at certain grade levels on learning some scientific ideas.[3] Bruner (1961) justified that many topics in mathematics--not topics in science--can be taught to school students through some representations that rest directly on the stages of students' intellectual development.[4]

The second warrant is the constraint--exercised by the ontological continuity and progression in the development of scientific discourse--on what ideas can be taught to learners at certain grade level. As already illustrated in

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[3] Bruner (1961) believed that "the child's intellectual activity seems to be based upon an ability to operate on hypothetical propositions rather than being constrained to what he has experienced or what is before him." (p. 37). This ability is characterized in terms of Piaget's intellectual stages of development. Bruner believed that at each stage of development the child has a characteristic way of viewing the world, and the task of teaching a subject is one of representing the structure of that subject in terms of the child's way of viewing things.

[4] The topics Bruner (1961) discussed include "set theory," "theory of function," "invariance," "projective geometry," and "probabilitic reasoning".

chapter two, the development of scientific discourse embodies an ontological continuity and progression from Realm 1 (human actual experience) through Realm 2 (human possible experience) to Realm 3 (beyond actual and possible experience). Realm 3 discourse is grounded in the Realm 1 & 2 discourse, and Realm 2 discourse is grounded in Realm 1 discourse. It testifies the truth that it is impossible to teach Realm 3 discourse without teaching Realm 1 & 2 discourse first,[5] and the truth that it is impossible to teach Realm 2 discourse without teaching Realm 1 discourse first.

Therefore, not every type 2 or type 3 idea in the discipline of physics can be taught to anybody at any age (without teaching him/her some type 1 ideas that provide necessary foundations) because of the constraint exercised by the ontological continuity and progression in the development of scientific discourse. Teaching ideas at the high level without teaching some corresponding ideas at the low level is intellectually dishonest to the discipline of physics because it violates the ontological continuity and progression in the development of scientific understanding.

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[5] Osborne (1996) made an insightful observation about the constraint of ontological continuity on what ideas can be learned by students of a particular age. He pointed out that on the one hand, some science educators had attempted to ontologically shift some entities, such as energy, from Realm 3 to Realm 1; on the other research evidence suggests that the topic is too difficult and abstract for anybody younger than 18 (Warren, 1983; in Osborne, 1996).

Bruner had evidently failed to consider the ontological continuity and progression in the development of scientific discourse in establishing his proposition. While he emphasized the key ideas in advanced branches of a discipline (in other words, the fundamental concepts or principles contained in Realm 3 discourse), he seemed to have neglected the key ideas which provided the foundations for learning the key ideas in advanced branches of a discipline (in other words, the basic concepts or principles contained in Realm 1 discourse).[6]

Claim 2. Knowing the structures of the discipline of physics does not guarantee that physics teachers have the specific kind of subject-matter knowledge needed for teaching school physics.[7]

My second claim is a challenge to the belief that science teachers need to know the structures of the

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[6] Bruner (1961) seemed to suggest that basic ideas are only contained in the advanced branches of a discipline. He believed that the fundamentals should be determined by distinguished scientists who work at the frontiers of their disciplines. Ma (1994) observed that the basic ideas which Bruner discussed how to present to elementary school students are all the principles from advanced branches of mathematics--such as topology, projective geometry, probability theory, and set theory--rather than from mathematics at the elementary school level.

[7] The specific kind of subject-matter knowledge needed for teaching is what we call *pedagogical content knowledge* (see Shulman, 1986; 1987) or *knowledge of subject-specific pedagogy* (see McDiarimid, Ball, & Anderson, 1989).

discipline of science inherent in scholarly discourse about what science teachers should know,[8] or a challenge to the belief that having a bachelor degree in science is sufficient to teach school science.[9] What the findings of this study reveal to us is that the key ideas in teaching *color, the speed of light,* and *light interference* at the high school level are markedly different in theory-types, source analogues, and representations from those in the intellectual discipline of physics. The differences imply three likely mismatches between the kind of subject-matter knowledge needed for teaching school physics and the kind of subject-matter knowledge which physics teachers acquire from the discipline of physics through majoring in physics.

The first mismatch is reflected in the theory-types of key ideas. The findings about the differences between the key ideas in teaching *color* and *the speed of light* at the high school level and the corresponding key ideas in the

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[8] Many scholars believe that in order to teach a subject, teachers need to know about the substantive and syntactic structures of the academic discipline of that subject (e.g., Shulman, 1986; 1987; Wilson, Shulman, & Richert, 1987; Grossman, Wilson, & Shulman, 1989; Wilson, 1988; Grossman, 1990).

[9] It has been widely assumed that if teachers hold a bachelor's degree, they would know enough about the subject they would teach (see Kennedy, 1990a, 1990b; McDiarmid, 1992; Ball & McDiarmid, 1989; Ball & Wilson, 1990). The current reform movement on teacher education pressed for more sciences and arts preparation through transforming traditional teacher education four-year programs into five year programs, in which all teachers were required to major or specialized in an academic subject matter (e.g., the Holmes group, 1986)

discipline suggest that what high school physics teachers learn from the discipline of physics most likely are type 2 ideas in form of theoretical models and mathematical language; however, what physics teachers need to teach at the high school level involves type 1 ideas in form of common-sense experience and descriptive language. Knowing type 2 ideas in the discipline of physics cannot assure that physics teachers are capable of teaching type 1 ideas in school physics.[10]

The second mismatch is evident in the source analogues used in the formulation of type 2 ideas. According to

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[10] My experience in learning to teach *color* and my interview with Mr. Kennedy provide testimonies for this assertion. As already mentioned in chapter three, I was unable to teach *color* for high school students even though I had one year of coursework on *Optics* at the college level. While I shared this experience with Mr. Kennedy during an interview, he responded,

> Well I agree with you wholeheartedly. Ah, I went through, got a master in physics, before I started to teaching. While actually my undergraduate degree was in electrical engineering....I can conclusively say, I learned more physics, my first year, then I did in my master. Good physics should be those surrounded everyday. Good physics what I feel, is important, good physics the students encounter, everyday. And you are right, color, you get through that, isn't mentioned in college texts....I have, you know, some professors who were regarded as great teachers. I never had a professor at all of my college physics ever took time on this kind of stuff....Basically my experience with college physics, almost like, applying math, rather than that is theoretical models, is applying math....I learned more good physics through teaching after I got my master degree, than I did all my years at the college level. (IT-Kennedy, 4/28/1996)

finding 2, for the type 2 ideas about *light interference*, the source analogue which high school physics teachers acquire from the discipline of physics is the electromagnetic model of light. On the contrary, the source analogue used in teaching high school physics is "water waves interference" (or "sound waves and sound interference"). Grasping the source analogues in the discipline cannot guarantee that physics teachers are able to teach type 2 ideas using the source analogue in teaching school physics.

The third mismatch is reflected in the representations or reformulations of a key idea. For the topic *the speed of light*, what physics teachers learn from the discipline of physics are the fundamental constant "$C=3 \times 10^8$ m/s" and perhaps some contemporary methods of its measurement. However, teaching *the speed of light* at the high school level requires a rich set of analogues and examples, as well as a recapitulation of the history which can convey the meaning of "how fast light can travel" and "how the speed of light was measured historically" to high school students. Knowing the representations of a idea in the discipline doesn't guarantee that physics teachers can represent and reformulate the idea successfully at the high school level.

The above three mismatches are manifestations of the distinction between the psychological and the logical structures of subject matter. What physics teachers need to teach in a classroom context is more related to the psychological structure of subject matter that is centered upon the needs and experiential world of school students, and that is formulated in a way that follows the historic development of subject matter. On the other hand, what physics teachers acquire from the academic discipline of physics is more akin to the logical structure of subject matter that is centered upon concepts and principles of high levels, and that is constituted by a body of finished outcomes of scientific understanding. Therefore, knowing the logical structure of the academic discipline of physics doesn't guarantee that physics teachers have the specific kind of subject-matter knowledge needed for teaching school physics.[11]

It is worth pointing out that this claim is parallel to the one made the National Center for Research on Teacher

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[11] Critics would argue that teachers can learn about this specific kind of subject matter knowledge by teaching it if they are smart enough and have a degree in the subject (see Zumwalt, 1991; Darling-Hammond, 1990; Kennedy, 1990b, for this argument). However, a substantial body of body evidence show that this kind of knowledge growth among beginning teachers is generally slow and incremental, and is related to the time required for these teachers to plan, gather resources, teach, reflect, and reteach specific topics with increased effectiveness and fluency. (Hashweh, 1987; Shulman, 1986, 1987, 1988; Wilson, Shulman, & Richert, 1987). NCRTL Researchers showed that beginning teachers with a bachelor's degree made no significant progress in acquisition of this kind of knowledge after the alternative route programs which provided their on-the-job training (e.g., NCRTL, 1991, 1993; Kennedy, 1990b; McDiarmid, & Wilson, 1991; Deng, 1994).

Learning (NCRTL): "Majoring in an academic subject in college does not guarantee that teachers have the specific kind of subject matter knowledge needed for teaching" (NCRTL, 1993, p. 2). In the Teacher Education and Learning to Teach (TELT) Study (see NCRTL, 1991, 1993; Ball, 1988), researchers asked teacher candidates to apply their subject-matter understanding as a teacher would. They found that teachers who majored in mathematics often were no more able than non-major to perform the tasks.

Claim 3. Key ideas in teaching school physics constitute an essential component of pedagogical content knowledge.

My third claim is a challenge to the wide spread belief about pedagogical content knowledge in which key ideas in teaching are not perceived as a component (see Chapter 1). Three warrants justify that key ideas in teaching school physics constitute an essential component of pedagogical content knowledge.

The first warrant is that key ideas in teaching school physics are a special form of subject-matter knowledge which can set physics teachers apart from physicists.[12] As revealed from the findings, in teaching a particular topic to students of a given age, what physics teachers teach are

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[12] According to Shulman (1987), pedagogical content knowledge is the special kind of subject-matter knowledge "most likely to distinguish the understanding of the content specialist from that of the pedagogue." (p. 8)

not the key ideas in the intellectual discipline of physics (or the key ideas for physicists), but the key ideas in teaching school physics which markedly differ in theory-types, source analogues, and representations from the key ideas in the intellectual discipline of physics. In other words, key ideas in teaching school physics is a special kind of subject-matter knowledge for physics teachers, and key ideas in the intellectual discipline is a particular form of subject-matter knowledge for physicists.

My second warrant is about the teachability embodied in key ideas in teaching school physics.[13] Prawat already (1989b) argued that key ideas in teaching play an important role in promoting the accessibility of knowledge to learners because key ideas can serve as anchors for students' cognitive structure which allow for a rich set of connections. According to my analysis, key ideas in teaching school physics stand for the psychological structures of subject-matter knowledge because 1) they are centered upon the experiential world of school learners; 2) they are formulated through models appropriate to the knowledge background of learners, and 3) they are selected and formulated in a way that reflects the historical epochs in the development of subject-matter knowledge. (This way of

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[13] Shulman (1986) believed that pedagogical content knowledge is "the particular form of content knowledge that embodies the aspects of content most germane to its teachability." (p. 9)

selecting and formulating key ideas, as already indicated in chapter six, embodies psychological and epistemological significance.) Key ideas in teaching school physics, thus, inherit the potential of enhancing the accessibility of the subject matter to learners. In other words, key ideas in teaching school physics embody the aspects of subject matter "most germane to its teachability".

The third warrant is that key ideas in teaching school physics provide an indispensable base upon which two other components of pedagogical content knowledge, pedagogical representations and instructional strategies, are identified or developed. The teaching philosophy of the most brilliant teacher of physics in this century, Richard Feynman, testifies the critical role of key ideas in reasoning about pedagogical representations and instructional strategies in teaching physics: "First figure out why you want the students to learn the subject and what you want them to know, and the method will result more or less by common sense." (Feynman, 1995 p. xx). What came to Feynman by "common sense" would be often some brilliant methods in form of pedagogical representations and instructional strategies that could perfectly convey the key ideas he wanted students to learn. For the two experienced physics teachers, Mr. Barnes and Mr. Kennedy, figuring out what key ideas were was also the starting point for developing effective pedagogical representations and instructional strategies. In explaining how to select and develop experiments, demonstration, and activities in physics teaching, Mr. Barnes said,

> I stop and ask myself what do I want as a outcome for the students, what do I want them to understand about the unit, so I look for main ideas, in that unit....I go through and identify what I think is the major concepts, major ideas, then I, then I, say well, what would be the best ways for students to learn about these ideas. Okay, if there is an experiment, okay, I try to develop the experiment, class discussion, discussion questions, homework problems. (IT-Barnes, 6/3/1996)

Mr. Kennedy stated,

> I think just to pick out what you think is the best match, the fundamentals, the important characteristics...and then develop materials that will bring your students alive, to expose to all of those....And I think my role is to provide audio, visual, or just tapes, ah, overheads, demonstrations, suggestions and that sorts of things. (IT-Kennedy, 4/28/1996)

To summarize, key ideas in teaching school physics constitute an essential component of pedagogical content knowledge because 1) key ideas in teaching school physics is a special form of subject-matter knowledge most likely to set the understanding of physics teachers apart from that of physicists; 2) key ideas in teaching school physics are closely related to the teachability of subject-matter knowledge; and 3) key ideas in teaching school physics are an indispensable base or starting pointing for reasoning about pedagogical representations and instructional strategies.

It is important to recognize two limitations of this study. First, the study doesn't try to describe and explain the differences between key ideas in teaching school physics and key ideas in the intellectual discipline of physics in an exhaustive way; rather, it only focuses on the key ideas in three topics, *color*, *the speed of light*, and *light interference*, in the domain of optics. What would be the findings or conclusions if we examine the key ideas in other domains--such as mechanics, electricity and magnetism, and molecular physics--or in other school subjects--such as chemistry, biology, and geology? Second, the framework of this study doesn't try to represent the structures and practice of science in some rather sophisticated fashion. It draws exclusively upon Harre's theory of *referential realism*. What would a more comprehensive framework developed based upon an extensive survey of philosophy of science and history of science entail for selecting and formulating key ideas in teaching school science?

Implications

Three implications can be drawn in light of the above conclusions and limitations. The first implication is for research on science teachers' pedagogical content knowledge. More empirical research is needed to investigate the nature and representations of key ideas in teaching school science (physics in particular). Key ideas in teaching school science are a special component of pedagogical content knowledge which is indispensable in the development of two other components of pedagogical content knowledge--pedagogical representations and instructional strategies. Thus, a thorough understanding of the nature of pedagogical content knowledge in school science requires extended investigations of the nature and representations of key ideas in science teaching, focusing on some core topics in school science curriculum. These investigations will provide some groundwork for the development of a special subject-matter sequence for prospective science and mathematics teachers that is the focus of my following discussion.

The second implication is for the education of science teachers. Because of the mismatches between the kind of subject-matter knowledge needed for teaching school physics and the kind of subject-matter knowledge which physics teachers acquire from the discipline of physics, a special subject-matter sequence is particularly needed for the education of science teachers (physics teachers in particular), in addition to the subject-matter sequence offered by the science departments at college or university. I believe this special sequence should focus on deepening and broadening prospective teachers' understanding of the key ideas in teaching core topics in school sciences. It should also enable teachers to understand some related epistemological issues (e.g., what is the nature of knowledge and how is it produced and validated?), psychological issues (e.g., what are difficulties students might encounter and what are common preconceptions or misconceptions hold by students?), and pedagogical issues (e.g., what are the effective ways of representing and reformulating the knowledge?). This sequence can be developed based upon the investigations of the nature and representations of key ideas and other empirical research about students' learning in school science, and also through an integration of history and philosophy of science, and contemporary theories of learning.

The last implication is for the construction of a science curriculum. We need to develop a theoretical base for the construction of a science curriculum that bears a transparent relationship to the structures and development of science. The lack of such a theoretical base had led to some serious confusions in the construction of a science curriculum. As already indicated, Bruner evidently failed to consider the constraint on the selection and sequencing of content in a science curriculum--exercised by the progression and ontological continuity in the development of scientific discourse--while advancing his proposition. Constructivist epistemology--which in its radical configuration is a misrepresentation of science as it is practiced--offers little guidance on the organization and sequencing of content within a science curriculum (Osborne, 1996).

Harre's account of three Realms of scientific discourse and ways of theorizing provides a tentative theoretical base for the construction of a science curriculum. The construction should follow the progression and the ontological continuity in the development of scientific discourse; that is, a curriculum should start with scientific discourse at the foundational level, build upon and extend students' experience of macroscopic phenomena, and eventually move toward an understanding of the entities in scientific discourse at a higher level through descriptive and non-sophisticated mathematical language. It can introduce students to the learning of some entities in scientistic discourse at the more abstract and quantitative level, based upon their understanding of the entities in discourse at the lower levels. I believe a more sophisticated theoretical base can be established through an extensive exploration of philosophy and history of science.

APPENDICES

APPENDIX A

APPENDIX A

TEACHER INTERVIEW PROTOCOL: THE FIRST INTERVIEW WITH MR. BARNES AND MR. KENNEDY

Questions about *color*

I realized that the topic color is not be very important in teaching optics at the college level, but is very important at the high school level.

* Why is *color* important in teaching optics for high school students?

* Why is color not important in teaching optics at the college level?

* What are the key ideas in teaching *color* for high school students?

* In what ways can learning these key ideas promote student's understanding about the nature of light?

Questions about *the speed of light*

I also realized that the topic the speed of light is not be very important in teaching optics at the college level, but is very important at the high school level.

* Why is *the speed of light* important in teaching optics at the high school level?

* What are the key ideas in teaching *the speed of light*?

Questions about *light interference*

* What are the key ideas in teaching *light interference* at the high school level?

* Teaching *light interference* at the college level is usually based upon Maxwell's equations. In your teaching, you started with water waves, sound waves, and then to light interference. I understand that the first approach doesn't work for high school students and the second approach seems to be the best for high school students. How do you think about these two approaches?

Question about teaching goals/objectives

I realized that the objective sheets are very helpful for students to understand some physics topics. Tell me about how you develop the objectives for each topic. Also tell me about why you develop the objectives for each topic.

* I remember you told me that the 1st hour class is a college preparation class. Could you told me about your teaching goals for these students?

* How are your goals for students related with the objectives on the sheets?

APPENDIX A

TEACHER INTERVIEW PROTOCOL: THE SECOND INTERVIEW WITH MR. BARNES

Questions about determine key ideas

Last time you told me that in developing objectives, you open the book, look at the section, ask yourself a question--"what are the main ideas you like students to know in this section?"--and then you write them down.

*What do you mean by main ideas?

*Are all these (refer to the teaching objectives about *color* on the objective sheet) the main ideas about color you expect students to learn?

*Within all these ideas, are there some more important ideas would you want students to learn about?

*In the trip to the auditorium, what the main ideas about *color* did you want students to learn through the demonstrations?

Questions about including key ideas

*You have included "particle theory," "wave theory," "photon theory" and "ether theory" to your teaching about light. What are your main reasons for including these topics?

*What are your main reasons for including "ether theory" to your teaching?

Questions about the criteria for selecting pedagogical representations

*In involving students to learn physics, you provided a lot of demonstrations, hands-on experiences, and video-tapes. What are your criteria for selecting these demonstrations, hands-on experiences, and video-tapes?

*Where do you get the video-tapes ?

Questions about preparation

At the end of each lesson, you always give students assignments for the next day. That includes reading the textbook, reading the supplemental booklets, and solving problems. I know that you want students to be well-prepared when they come to the classroom

*Why do you think "being well-prepared" are important for students to learn physics?

*How many students do you expect would do the readings every time?

<u>Questions about the key ideas in teaching *light interference*</u>

*What are the main ideas you would like students to learn about *light interference*? Why do you think they are important for students?

*Why is the question--"how can the wavelength of light be determined experimentally?"--the central question in your teaching?

*In organizing students to do the Young's experiment, what do you expect them to learn or to be able to do (tell me as more as you can)?

APPENDIX A

TEACHER INTERVIEW PROTOCOL: THE SECOND INTERVIEW WITH MR. KENNEDY

Questions about determining key ideas

Last time you told me that in preparing to teach physics, you pick up the fundamentals and the important characteristics in different areas of physics, and then develop the materials.

*What do you mean by the fundamentals and the important characteristics?

*How do you determine the fundamentals and the important characteristics for teaching?

*In what way would you think the texts or curricular materials are helpful for you to identify the fundamentals and the important characteristics for teaching?

Questions about the key ideas in teaching *color*

In teaching color, you had focused on four key ideas: 1) the correlation between color and frequency; 2) color substraction; 3) color addition; and 4) why the sky is blue. It appears to me that it is very well-conceptualized. I want to understand the way of your organizing the content.

*Why did you prefer the term "color substraction," rather then "color absorption"?

*The text first starts with "color by reflection" and "color by transmission" and then goes to "color mixing by addition" and "color mixing by substraction." What are the main reasons that you focused your instruction on "color addition" and "color substraction"?

*In teaching "color addition" and "color substraction," all the questions in your packet, all the demonstrations and overhead you provided in the class, I felt they just spoke to the points or the concepts. Can you tell me what your criterions are in selecting or developing these questions, demonstrations and overheads?

Questions about the key ideas in teaching *the speed of light*

In the text and your packet, there are information about the measurement of the speed of light, and about the dual nature of light.

*Why didn't you talk about the measurement of the speed of light this time?

*In your opinions, in what ways can the history about the measurement of the speed of light be important for the students?

*Are you going to talk about the "dual nature of light" at the end of this semester? In your opinions, in what ways can the "dual nature of light" (wave theory and particle theory) be important for students to understand the nature of light?

<u>Questions about the key ideas in teaching *light interference*</u>

It is unfortunate that I am unable to learn about how you approach to the topic *light interference*. Here I hope you can just respond to some of my questions.

*What are the key ideas in *light interference* you would like your students to expose to?

*Why do you think these ideas are important for students?

*How do you approach to teaching *light interference*?

*In organizing students to do the Young experiment, what do you want students to learn from the experiment?

APPENDIX B

APPENDIX B

PROFESSOR INTERVIEW PROTOCOL: THE FIRST INTERVIEW WITH PROFESSOR A

Introduction

I am working on a dissertation about the nature of key ideas in teaching physics. I am making a comparison between teaching optics at the high school level and at the college level. I am trying to understand how some key ideas in teaching at the high school level are different from those at the college level and why they are different.

Some general questions

*What kind of optics course have you been teaching in the physics department?

*What are your purposes for teaching optics?

*Who are the students?

*What are your goals for the students?

*What are the most popular optics texts in the US?

*What are the most fundamental concepts, principles, and theoretical models in physical optics? And why are they so fundamental?

*What kind of knowledge background in physics and mathematics would you expect students to have in learning about these fundamental concepts and principles?

Teaching *color*

In observing teaching optics at the high school level, one of the interesting thing I found is that the topic *color* is very important for high school physics. The key ideas involve "the combination of white light," "color by reflection," "color by transmission," "color mixing by subtraction," and "color mixing by addition." However, this topic appears to be not important in teaching optics at the college level.

*Why is *color* not an important concepts in teaching optics at the college level?

*How would you teach the ideas "reflection," "absorption," and "transmission"?

*How would you communicate or represent the interaction of light waves with materials to college students?

Teaching *the speed of light*

In observing teaching optics at the high school level, another interesting thing I found is that *the speed of light* is a an important topic. Yet in teaching optics at the college level *the speed of light* appears to be not an important topic.

*Why *is the speed of light* not an important topic in teaching optics at the college level?

*How would you teach *the speed of light* at the college level?

*Did you teach about how scientists measured *the speed of light* in the past?

Teaching *light interference*

*What are the key ideas in teaching *light interferences* at the college level?

*How did you teach *light interference* for physics students?

*How would you represent the interaction of light waves?

*In teaching *Thomas Young's experiment* (2-sources interference) for physics students, what did you want them to learn about the experiment?

*Suppose you are organizing college students to do the experiment, what would you want them to learn from the experiment?

APPENDIX B

PROFESSOR INTERVIEW PROTOCOL: THE SECOND INTERVIEW WITH PROFESSOR A

Questions about *color*

Last time I told you that I am trying to understand the difference between teaching optics at the high school level and at the college level. One thing I found is that *color* is very important topic at the high school level. The basic ideas include "the relationship between different colors and different frequency or wavelength of light," "color by reflection," "color by transmission," "color mixing by subtraction," and "color mixing by addition." And yet it appears that these ideas are not being taught at the college level.

*How do you think the about *color* is not an important topic in teaching optics at the college level?

*When I asked high school teachers why *color* was a important topic for high school students, they told me that "color" is a big part of their world, they saw examples everyday, and they enjoyed learning it. Do you think college students would also enjoy learning about *color*?

Questions about *the speed of light*

Another thing I found was that *the speed of light* is an important topic in teaching optics at the high school level. High school teachers try to help kids understand and appreciate how fast light can travel, and how the speed of light was measured by scientists in the history. And yet in college physical optics, *the speed of light* appears to be not a key topic.

*From the point of view of the academic discipline, how do think *speed of light is* not a key topic in college optics?

*How would you teach *the speed of light* for college students?

*High school teachers told me that high school students would be interested in knowing how people measure *the speed of light*. Do you think college students would be interested in knowing how to measure *the speed of light*?

<u>Questions about *light interference*</u>

Last time you told me that teaching *light interference* at the college level is based upon the idea of coherence and electromagnetic theory of light. High school teachers follow the sequence of water waves interference, sound waves interference, and light interference.They regard it as a "logical and natural sequence" because students don't have enough background in electromagnetic theory and mathematics.

*How do you think about such a sequence?

*Do you think people need to follow this sequence in order to understand about *light interference*?

<u>Questions about college texts</u>

*What are the textbooks you require students to read in your course?

*It is very interesting that in other discipline, such as history and literature, college students need to read some kind of classic literature. It appears to me that physics student don't need to read classic. They only need to read textbook. How do you think about it?

APPENDIX B

PROFESSOR INTERVIEW PROTOCOL: THE INTERVIEW WITH PROFESSOR B

Introduction

I am trying to get a better understanding about the nature of key ideas in teaching optics at the high school level. For this purpose, I have been examining and comparing the differences between teaching optics at high school level and at the college level. I am also trying to explain why they are different.

Some General questions

* What kind of optics course have you been teaching? Why do you teach optics?

* Who are the students? What are your goals for your students in teaching optics at the college level?

* What kind of understanding would you expect students to develop from physical optics?

* What kind of knowledge background and experience would you expect your students to have in order to do well in optics?

* What are the key ideas (concepts or principles) in teaching optics at the college level? In what sense are they key ideas?

Questions about *color*

When I observed teaching optics at the high school level, I found that *color* is an important topic. The basic ideas include "the combination of white light," "color by reflection," "color by transmission," "color mixing by subtraction," and "color mixing by addition." And yet it appears to me that these ideas are not taught at the college level.

* How do you think that *color* is not an important topic at the college level?

* When I asked high school teachers why *color* was an important topic for high school students, they justified that "color" was a big part of their world, they saw examples everyday, and they enjoyed learning it. "Color" is also a part of physical world for college students, why

color is not important for college students as compared to high school students?

* Some ideas such as "reflection," "transmission," and "absorption" that are important in understanding about *color* at the high school level. I found that these ideas are also important in teaching optics at the college level. How would you teach these ideas?

<u>Questions about *the speed of light*</u>

Another thing I found was that *the speed of light* is an important topic in teaching optics at the high school level. High school teachers try to help kids understand and appreciate how fast light can travel, and how the speed of light was measured by scientists in the history. And yet in college optics *the speed of light* appears to be not a key topic.

* From a theoretical perspective, how do you think *the speed of light is* not a key topic in teaching optics at the college level?

* How would you teach *the speed of light* for college students?

* Teaching optics at high school level deals with how people measure light in the past. It appears to me that this piece of information is not important in teaching optics at the college level. How do you think about it? How do you teach college students about the measurement of the speed of light?

<u>Questions about *light interference*</u>

* What are the key ideas in teaching *light interference* at the college level? In what sense are they key ideas?

* How would you teach *light interference* at the college level?

* High school teachers follow the sequence of water waves interference, sound waves interference, and light waves interference in teaching *light interference*. They regard it as a "logical and natural sequence" because high school students don't have enough background in electromagnetic theory and mathematics.

*How do you think about such a sequence?

* Do you think people need to follow such sequence in

order to understand *light interference*?

* What demonstrations would you probably do in teaching *light interference*? Or what kind of experiment would you like students to do in lab about *light interference*? What do you want students learn from the demonstration or experiment?

Questions about texts

*What are the texts books you require students to read in your course?

*It is very interesting that in other discipline, such as history and literature, college students need to read some kind of classic literature. It appears to me that physics student don't need to read classic. They only need to read textbooks. How do you think about it?

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