A THEORETICAL FRAMEWORK FOR THE INCORPORATION OF HISTORY IN SCIENCE EDUCATION

BY

JAMES STEPHEN KLASSEN

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
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ABSTRACT

This thesis formulates a theoretical framework for the incorporation of history of science in science teaching, which, it is argued, is essential to laying a stable foundation for instructional design and future empirical studies.

It is assumed that the historical approach to teaching science no longer needs defending and that contextual methods are a pedagogically sound approach to learning. Various cognitive and learning theories suggest that there are five distinct contexts that are important in engaging learners: the theoretical, practical, social, historical, and affective. On the basis of these five contexts, a model for teaching and learning is constructed, in which the story assumes a major role in engaging the learner affectively. This model is named the Story–Driven Contextual Approach (SDCA). The SDCA is introduced to students by means of a narrative, encouraging students to become actively engaged with the five contexts. In the SDCA, students are seen as novice researchers and the teacher as a research director.

The place and nature of the historical science story in science education is a relatively undeveloped area in the literature. This thesis argues that the development of the events in a story proceed in the same fashion as the steps in learning a concept. A structural model of a story consisting of a three–stage temporal sequence, which includes a causative element, is presented and developed. It is argued that the conceptual change process, from a temporal perspective, can also be viewed as a three–stage sequence similar to the story. The story can, in this light, be thought of as the re–enactment of a particular type of learning process. This knowledge about the nature of stories can serve as a guiding principle in the designing and writing of effective stories based on the history of science, which are to be incorporated with the SDCA.

The SDCA was tested in a university physics class using a constructed story which portrays the heroic personal and scientific efforts of the nineteenth century physicist Lord Kelvin in laying the first successful trans–Atlantic cable. Students designed and undertook various practical and theoretical exercises in the SDCA and observations on its implementation are reported.

ACKNOWLEDGMENTS

I wish, first of all, to acknowledge the wisdom and insight that was provided by God, in answer to my prayers, in order for me to carry out this work. Secondly, I am supremely grateful for the encouragement, advice, and assistance that was provided by my loving wife, Cathrine. Then, I acknowledge Dr. Arthur Stinner, who, with his vision, enthusiasm, and advice, changed the course of my academic life when we met and has become a friend for life. Finally, I thank the University of Winnipeg for assisting my studies through the granting of a most valuable educational leave.

Chapter 1

INTRODUCTION

> Pat had just been introduced to me as a real estate agent. "Pleased to meet you", I said, as I shook Pat's hand. Pat responded, "And what do you do?" That was the usual question and I anticipated the usual response to my answer: "I teach physics at the university." "Physics, eh? That was always my worst subject." How do I respond this time? I will be straightforward. "Well, we make physics difficult by what we believe about it and how we teach it. In my work, I'm trying to find ways of making physics both attractive and understandable to students." Pat smiled. "I wish I'd had a teacher like you when I was in school." (Personal anecdote.)

During the past decade, or so, university science departments, especially physics departments, have experienced a decline in enrolments that has encouraged self–examination. In the process of self–examination, researchers have discovered that science lectures, especially in physics, tend to be unpopular (Brouwer, Austen, & Martin, 1999; NSF, 1996). The phenomenon of unpopularity appears to be widespread, as German educators also observe that "science (except biology) and mathematics are the most unpopular subjects in German schools, where physics is disliked most" (Riess, 2000, p. 328). Brouwer, et al., pinpoint a major issue contributing to the present state of affairs, namely that physics educators "have, in general, not been successful in convincing students that physics is alive, changing, and dynamic, and that research in physics has been carried out by human beings, with aspirations, doubts and conceptual difficulties not too different from those of our students" (1999, p. 365). According to a major National Science Foundation study published in 1996, the situation in the sciences is serious and requires fundamental changes in our attitude and approach to teaching science at the university level. The report concludes that "we can no longer be satisfied with incremental improvement in a world of exponential change" (NSF, 1996). It was against a background of similar concerns that I attended the *Second International Seminar for the Use of History in Science Education*, in Munich, Germany, in 1998, where Swiss educator, Fritz Kubli, reported on research exploring and listed arguments for the use of stories from the history of science in teaching physics (Kubli, 1998a, 1998b). The ideas presented at that seminar stimulated the thought process that has led to the researching and writing of this thesis.

The purpose is to develop a theoretical framework for the incorporation of history of science in science education, primarily, by using the story form. To narrow the scope and to reflect the area of expertise of the author, examples and applications in science education will be restricted almost exclusively to those in physics; however, the research used to arrive at the framework is drawn from many disciplines and many areas of science education, not just physics. Consequently, the applications and generalizations of the thesis will include other sciences. In this introductory chapter, a context for the thesis will be set. First, the origin of the notion of linking history of science to the study of science will be examined, based on the assumption that studying the origins of any idea is important to the understanding of that idea. Since the goal of scientific literacy is being espoused today by the major policy agencies in science education that influence curriculum design, the idea of scientific literacy will be examined.

The Origins of the Relationship between History of Science and Science Education

The complementary ideas that science learning parallels the history of science and that the use of history of science can promote learning have existed for a long time. The great Scottish physicist, James Clerk Maxwell (1831–1879), expressing this view, wrote in the preface to his collected works that "it is of great advantage to the student of any subject to read the original memoirs on that subject, for Science is always most completely assimilated when it is in the nascent state" (1873/1904, p. xi). The idea that science should be taught through its history is consistent with the arguments of the theory of *recapitulation.* This theory, which was popular in Maxwell's day, contends that ancestral development over a long period is repeated cumulatively in the individual many generations later.

The Theory of Recapitulation

Toward the end of the eighteenth century, what philosopher R. G. Collingwood calls the "modern view of nature" began to emerge and it contributed to the development of the theory of recapitulation (Collingwood, 1945; Gould, 1977). History was considered a continuously evolving process that does not repeat itself, but is progressive. This idea of history, according to Collingwood, had an effect on ideas about nature. Many subsequent theories in science were "based on the analogy between the processes of the natural world as studied by scientists and the vicissitudes of human affairs as studied by historians" (Collingwood, 1945, p. 9). According to this line of reasoning, what happens in the natural world at the phenomenological level must be similar, at least in some respects, to what takes place in the dynamics of human affairs, which, it is assumed, are well understood. The affairs of men will reflect some aspects of the laws of nature, whatever they are, and the same natural laws will affect individual development throughout history. Since we observe the course of history to be continuously changing, we would assume this also to be the case for nature. Consequently, the processes of nature, like the processes in history, are viewed not as cyclical but as progressive. The abilities or thought processes that humans have acquired in the course of the development of the species are seen as features of the process of building greater complexity. The features that were developed in primitive generations still reside in the offspring many generations later and can today be observed in children.

According to Stephen Jay Gould, recapitulation first became significant in its formulation by the German Naturphilosophen, among them, notably, Johann Wolfgang von Goethe (1749–1832) (Gould, 1977, p. 35; Schmidt, 1909, p. 156). One can see in the thought of Goethe something of the "modern" view of nature described by Collingwood. Goethe was much devoted to studying and writing about nature (Jaki, 1969). He maintained that "nature proceeds according to idea just in the same way as man follows an idea in all that he undertakes" (Goethe, in Steiner, 1897/1973, p. 37) so that history develops progressively, though unpredictably, according to natural laws. In nature, Goethe wrote, "was da ist war noch nie, was war kommt nicht wieder – alles ist neu, und noch immer das Alte" (Goethe, 1783/1955, p. 5) or "what is there, never was; what was, never will return. All is new, and yet forever old" (Goethe, 1988, p. 3). In 1794, the German poet Schiller, in a letter to Goethe, explained his reading of Goethe's view of nature, stating that "from the simple organism you ascend step by step to the more complex, in order finally to build up the most complex of all, man, genetically from the materials of the entire structure of nature" (Schiller, in Steiner, 1914, p. 52). Goethe sought to apply the same methods of explanation to both living organisms and inorganic nature. Hence, the development of behaviour patterns and knowledge in the species was subject to the same considerations as the development of the physical characteristics of the species. Later in his life, Goethe articulated the recapitulation idea explicitly, writing, "Wenn auch die Welt im ganzen vorschreitet, die Jugend muss doch immer wieder von vorn anfangen und als Individuum die Epochen der Weltkultur durchlaufen" (in Schmidt, 1909, p. 156) or "Even if the world, as a whole progresses, young people must still start at the beginning and traverse the epochs of world culture" (S. Klassen, Trans.). It is not difficult to see, in Goethe's philosophy, the parallelism between history and nature that Collingwood described, where the growth of both biological and psychological complexity in the species parallels the historical growth of ideas.

The theory of recapitulation was expressed both in the context of the development of knowledge and in the context of biology. In the context of biology, the theory related the physical development of the individual to the development of primitive ancestors. The nineteenth century theory of biological recapitulation could be defined as "the repetition of ancestral adult stages in embryonic or juvenile stages of descendants" (Gould, 1977, p. 485). Controversial German biologist Ernst Haeckel (1834–1919) invented the phrase "ontogeny recapitulates phylogeny" to describe recapitulation, adapting ideas first put forward by biologist von Baer (Gould, 1977; Veltman, 2000). Haeckel's model also became known as the "biogenetic law". However, in the first quarter of the twentieth century the theory of biological recapitulation was decisively discredited (Davidson, 1914; Garstang, 1922; Gould, 1977; Rasmussen, 1991) and other theories were being sought to explain individual development.

Recapitulation in the context of knowledge will be referred to as psychological recapitulation. Here recapitulation deals with the growth of knowledge or behaviour patterns in the individual. Psychological recapitulation was popularized by the philosopher Herbert Spencer (1820–1903). Spencer wrote that

> if there be an order in which the human race has mastered its various kinds of knowledge, there will arise in every child an aptitude to acquire these kinds of knowledge in the same order. … Education should be a repetition of civilization in little. (1861, p. 76)

Both Sigmund Freud (1859–1939) and Carl Jung (1875–1961) adopted views similar to those of Spencer, which they incorporated into their philosophies. Freud believed that "each individual somehow recapitulates in an abbreviated form the entire development of the human race" (Freud, 1916, p. 199). Freud's view justifies an approach to history that uses childhood behaviour to interpret ancient history and on this basis reconstruct history based on observations of the development of children. If children's thinking, indeed, contains ancient history in a microcosm, then the study of children may be a shortcut to historical research. This method was used by Thomas Kuhn on occasions when he found historical analysis particularly difficult, whereupon he resorted to describing the behaviour of children to illustrate the (supposed) behaviour of early scientists (Kuhn, 1977).

On the other hand, Jung believed that "the child lives in a pre–rational and above all in a pre–scientific world, the world of those who existed before us" (Jung, 1943, p. 134). If the world of the child is already known in ancient histories, then the development of the child must follow historical development. Jung's approach lends itself to curriculum design and advocates the use of history as a guide for how to teach children. In his early work, Dewey used a curriculum that began with Greek myths in primary school and progressed to Roman law (Gould, 1977, p. 154). This approach was soon abandoned, as, on the one hand, it was a failure, and on the other hand, Dewey developed strong objections to recapitulation on philosophical grounds. Although controversial at the time, these views of childhood and history influenced the later work of both Piaget and Kuhn.

The psychological theory of recapitulation as expressed by Spencer, Freud, Jung, and others was closely tied in its origin and justification to the biological theory of recapitulation, especially to the biogenetic law of Haeckel. Proponents of psychological recapitulation inferred their theory from biological recapitulation. Since they considered biological recapitulation to be a confirmed scientific theory, they, in turn, had confidence in psychological recapitulation. When the biogenetic law was shown to be invalid, the psychological theory of recapitulation was not abandoned but became difficult to justify after that. An attempt to adapt the ideas of psychological recapitulation was made by German gestalt psychologist Kurt Koffka (1886–1941), who reformulated the idea of recapitulation by proposing a correspondence theory in which ontogeny seems to parallel phylogeny only because similar external constraints operate on both (Koffka, 1931). One can see here a foreshadowing of the view later expressed by Piaget. Piaget, through his systematic study of young children, came to the conclusion that children's thinking normally develops in a structured fashion and that these developmental patterns are fundamental.

A common element among various recapitulationist theories is the importance of teaching successively more modern historical views as a means of paralleling the development of the child's thinking. For example, recapitulationists would recommend that force be taught by beginning with the concept of force as impetus, followed by the concept of action–at–a–distance, followed by the concept of force as curvature of space–time (see Stinner, 1994 for a discussion of the evolution of the concept of force). Recapitulation, in using the history of science as a device to teach science, promised to provide a scientific basis for science education.

Science, History of Science, and a Liberal Education

The idea of a liberal education probably originated in classical Greek civilization. Plato advocated education as a means of advancing the happiness and harmony of the soul and of promoting a just society. Towards this end he listed a wide–ranging curriculum that was designed to provide the student with a well–rounded education. Throughout the Middle Ages education was designed to be liberal in nature by attempting to preserve elements of Greek and Roman civilization. The nineteenth century saw a resurgence of the liberal view of education at about the same time that Herbert Spencer was developing his recapitulationist ideas. Thomas Huxley in his 1868 essay, "A Liberal Education and Where to Find It", argued for a well–rounded education in which the sciences are studied alongside the social sciences and the humanities. The motivations of Huxley and Spencer were, however, quite different. Spencer was concerned with the rhetorical question, "What knowledge is of most worth?" with "science" as the obvious answer. Huxley was more concerned with the development of the individual in a way that would enhance personal fulfillment. Both Huxley and Spencer advocated the studying of science, but Huxley assigned a much different role to science than did Spencer, who scoffed at the study of the humanities on utilitarian grounds. Huxley wanted the humanities and sciences raised to an equal level.

The ideal of a liberal education was taken up more recently at Harvard University by its president James Conant (1893–1978). History of science had begun to emerge as a discipline in North America in 1936 when Harvard University became the first university to offer a History of Science PhD. In the academic environment at Harvard, history of science developed as a discipline and science was taught in the context of its history. The commitment of Conant to the ideals of a liberal education, undoubtedly, helped provide the incentive and environment for history of science to flourish. Under the leadership of Conant, Harvard developed a vision for a liberal science education. In 1945, a Harvard committee issued a report describing this vision, which stated that

> the facts of science and the experiences of the laboratory no longer can stand by themselves, since they no longer represent simple, spontaneous, and practical elements directly related to the everyday life of the student. As they become further removed from his experience, more subtle, more abstract, the facts must be learned in another context, cultural, historical, and philosophical. Only such broader perspectives can give point and lasting value to scientific information and experience for the general student. (Conant, 1945, p. 156).

A conceptualization of the contextual approach to science teaching and its justification was one aspect of the report of Conant's committee, which had been set up to formulate Harvard's perspective on a liberal education. This approach to science teaching characterized much of the work of Conant and, later, that of the Harvard graduates Gerald Holton and F. James Rutherford. In the 1960's, Holton and Rutherford, together with Rutherford's PhD supervisor, Fletcher G. Watson, produced *Harvard Project Physics* (1970), the first high–school physics textbook that explicitly uses history of science (Holton, 1999, p. S105). Holton and Rutherford, together with David Cassidy have re–written the original *Harvard Project Physics* and the book is to appear, soon, under the title, *Understanding Physics.*

Learning science and the history of science were originally linked in the above two senses. First, they were linked by the recapitulation theory and then by the ideal of a liberal education, which embraced the contextual approach. Since then, the approaches and justifications for incorporating history of science in teaching science have proliferated.

Scientific Literacy as a Guiding Goal of Science Education Today

The idea of the importance of a general scientific understanding is a very old one, going back, according to Gerald Holton, as far as Plato's *Republic* (Holton, 1999). The pursuit of education, according to Plato, benefited the individual soul and thereby equipped the person to contribute to society in a productive fashion. An important element in Plato's curriculum was Mathematics, which contained in it Astronomy. However, in the nineteenth century, when science reached the point of influencing society as a cultural force in its own right, the idea arose that the study of science was central to a good education. One can see the idea that studying science is necessary for general well–being in the nineteenth century writings of Herbert Spencer.

James Conant was one of the earliest to use the term "scientific literacy" when he wrote the foreword to the proceedings of a workshop on science in general education held in 1952 (Cohen & Watson, 1952). Conant and his Harvard faculty had already set the groundwork for the notion of scientific literacy in the influential 1945 book *General Education in a Free Society*. There the idea that all members of society should have a basic understanding of science was presented. Later, Paul Hurd of Stanford University used the term "science literacy" in his ground–breaking article "Science literacy: Its meaning for American schools" (1958).

By 1995, Morris Shamos could state that "the goal of scientific literacy has become almost synonymous with today's science teaching" (p. 158) although Sutman responded with the opinion that it was premature to assign this high a status to the goal of scientific literacy (Sutman, 1996, p. 459). Yet, since then, scientific literacy has continued to gain stature in the guiding curriculum frameworks in North America. A search of the ERIC database on the key–words "scientific literacy" over the period 1980 to 1999 shows that activity in the field has continued to grow in a sporadic fashion (see Figure 1).

Although much work is being done in the area of scientific literacy, there is no agreed upon definition (Eisenhart, Finkel, & Marion, 1996; Matthews, 1994; Stinner,

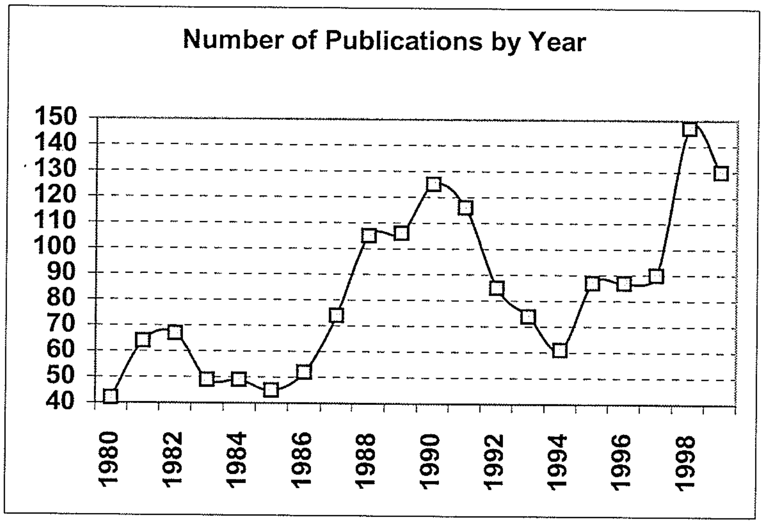


Figure 1: Number of Publications in Scientific Literacy

1992). There are almost as many definitions of scientific literacy as there are publications in the area. Most attempts at defining scientific literacy consist of a list of what the scientifically–literate person must know, abilities they must have, and attitudes they must exhibit, and almost all of them include understanding the nature of science.

Research and scholarship in the area of the nature of science (NOS) is a sub–specialization in its own right, even though understanding the NOS is traditionally considered a part of scientific literacy. Like scientific literacy, the NOS also defies definition. The term "nature of science" usually refers to the epistemology of science, and values and beliefs inherent to the scientific enterprise (Lederman, 1992). Usually, NOS statements claim that science is tentative, empirically based, and socially and culturally embedded (Lederman, 1998). Beyond that, understanding the NOS requires an understanding of the difference between observation and inference, and between theories and laws. Both scientific literacy and the NOS claim that the aim of science education should be to study *about* science (how science is made) in addition to studying science content.

The most influential definitions of scientific literacy in the United States are those contained in *Science for All Americans*, by Rutherford and Algren (1990), *Benchmarks for Scientific Literacy* by the American Association for the Advancement of Science (1993), and *National Science Education Standards*, by the National Research Council (1995). In Canada, the most influential document delineating scientific literacy is the *Common Framework of Science Learning Outcomes: Pan–Canadian Protocol for Collaboration on School Curriculum*, by the Council of Ministers of Education, Canada (1997). Unlike the guiding documents in the United States, the Canadian document has legislative force when enacted in the form of curriculum mandates in the legislatures of the provinces. The guiding documents carry considerable weight and it is common for them to be used as justifications for various approaches in education.

Perhaps the most concise definition of scientifically–literate persons is that they "... not only possess knowledge, but they use their knowledge in varied contexts and for worthwhile purposes" (Eisenhart, Finkel, & Marion, 1996, p. 282). The definition of scientific literacy of the Pan–Canadian Protocol, in a somewhat more detailed fashion, states that

> scientific literacy is an evolving combination of the science–related attitudes, skills, and knowledge students need to develop inquiry, problem–solving, and decision–making abilities, to become lifelong learners, and to maintain a sense of wonder about the world around them. (1997, p. 4)

Most other definitions of scientific literacy consist of detailed lists of knowledge or attributes and these will not be repeated here. A main constituent of various definitions, beyond specific knowledge requirements, is that persons continue to acquire new knowledge and that this knowledge be used in varying situations that include the practical.

The approaches to scientific literacy can be divided into two general classes: those with short–term instrumental goals and those with long–term process–oriented goals (Maienshein with students, 1998, p. 917). Matthews, in a view similar to that of Maienshein, earlier refered to the first class as a professional definition and to the second as a liberal one (Matthews, 1994, p. 32). The instrumental goals focus on the ability to recall key concepts in science, motivated by the needs of society for productivity. The process–oriented goals focus on developing scientific habits of mind, motivated by the need for personal fulfillment. Maienshein points out that the process–oriented goals include the ability to recall key concepts, but that if the knowledge goals become an end unto themselves, they do not imply the possession of a scientific attitude.

The idea of a liberal curriculum as one motivation behind scientific literacy emerges in a 1987 article by Paul Hurd where he writes that

> a measure of scientific literacy is a measure of cultural awareness. The traditional science curriculum leaves students as foreigners in their own culture. A problem in bringing about the essential reform of science teaching is that there are too many scientists who are scientifically illiterate and too few philosophers, sociologists, and historians of science and technology who are interested in precollege science education. (1987, p. 136)

Moreover, the "popular, contemporary, cleaned–up, and prejustified accounts of the behavior of the natural world" (Monk & Osborne, 1997, pp. 405–406) leave students unable to make connections between concepts and either their origin or application. The liberal view of education reacts to the status quo and contends that education is primarily for the benefit of the individual, as opposed to the benefit of society, and consequently tends to be inclusive and contextual in nature (Matthews, 1994). In Hurd's statement, consistent with the liberal view, the individual will find his or her place in the culture, thereby producing a sense of self–fulfillment. A liberal science curriculum is one that has been enriched by contributions from philosophers, sociologists, and historians of science who produce an inclusive and contextual view of science. Historian of education Lawrence Cremin prefers to refer to the liberal view of literacy as "liberating literacy" and observes that

> liberating literacy … meant that people could read freely and widely in search of whatever information and knowledge they chose. It also meant that literacy could serve a multitude of purposes in a multitude of ways. (1988, p. 658)

Cremin elevates the role of self–fulfillment to one of self–liberation and points out that the connections and contexts in a liberal education will act to serve diverse purposes in the end.

In the liberal view of scientific literacy, it is natural to find a role for history of science. *Science for All Americans* makes the connection between scientific literacy and history of science explicit by including a chapter on historical perspectives. Two kinds of arguments are made for the role of history of science—the contextual argument and the cultural argument. The contextual argument is promoted by *Science for All Americans* as an important factor in gaining an understanding of the nature of science. *Science for All Americans* states that

> generalizations about how the scientific enterprise operates would be empty without concrete examples. Consider, for example the proposition that new ideas are limited by the context in which they are conceived; … Without historical examples, these generalizations would be no more than slogans, however well they might be remembered. (Rutherford & Algren, 1990, p. 111)

Furthermore, the cultural significance of history of science is emphasized by *Science for All Americans* when it states that "some episodes in the history of science are of surpassing significance to our cultural heritage" (p. 111). The goals of scientific literacy, as summarized here, are consistent with the two arguments that were developed originally for linking science teaching with history of science, namely, the recapitulation view and the liberal view, the former providing a scientific basis and the latter providing a humanistic basis for pedagogy by the inclusion of history of science in science education.

Chapter 2

HISTORY OF SCIENCE IN SCIENCE EDUCATION:
A LITERATURE REVIEW

In 1974, historian of science Stephen Brush asked the partly tongue–in–cheek question, “Should the History of Science Be Rated X?” (Brush, 1974). In his article, he submits examples of how the current approach to history of science subverts the “whig” approach to history, which tends to present history in light of current “more enlightened” approaches to knowledge about the world. Furthermore, Brush demonstrates that detailed analysis of history shows that scientists are not always “rational” in their approach and do not always employ a specifiable scientific method. Brush concludes, somewhat facetiously, “that the teacher who wants to indoctrinate his students in the traditional role of the scientist as a neutral fact finder should not use historical material of the kind now being prepared by historians of science” (p. 1170). A few years later, Ian Winchester again raised the question of including history of science. He argues in a 1989 editorial that “to contribute intelligently to the discussion of the place of science in civilization and culture, one requires a well–grounded picture of the past, including the scientific past. And an education in science with no sense of its past or of the past generally will not provide such a picture” (Winchester, 1989, p. v). Contrary to Brush’s conclusion, Winchester recommends, in a more serious manner, that “if the schools are to support such a democratic society, then science must, it seems, be taught in such a way that is seen ‘warts and all.’

And only the history of science can offer that ..." (1989, p. v). The editorial is followed by an invitation for readers of the journal to attend the First International Conference on The History and Philosophy of Science in Science Teaching, later that year. Since 1989, the literature relating history of science and science education has seen a resurgence. That year, the International History, Philosophy, and Science Teaching Group was formed. The Group publishes the international journal *Science and Education*, which is dedicated to History, Philosophy, and Science Teaching.

The literature linking history of science and science education has concentrated on various justifications and approaches for using history of science in science teaching and on obtaining empirical support for doing so. Building up to the present, there has been a long succession of influential thinkers, among them Goethe, Freud, Koffka, and Piaget, whose work has contributed to establishing a theoretical basis for including history of science in science teaching. Among the recent proponents of this instructional strategy, the most influential scholars have been Gerald Holton and Michael Matthews. Today, a host of empirical and theoretical researchers are dedicated to the project of linking history and philosophy of science and science education. In this chapter, the respective literature is reviewed and the arguments for using history of science are categorized into four broad groups, partly based on categories proposed by Ian Winchester (1989): the scientific, pedagogical, cultural, and philosophical arguments.

The Scientific Argument

One of the original motivations for including history of science in science teaching, introduced in the previous chapter, was based on the recapitulation argument. The argument is essentially a scientific one because it attempts to show that there is a fundamental linkage between the development of science and science learning. John Dewey recognized the significance of the recapitulation argument in providing a basis for constructing curriculum other than tradition. Even though Dewey later was a detractor of recapitulation (see his *Democracy and Education*, 1916), he admitted that "educational theory is indebted to the doctrine for the first systematic attempts to base a course of study upon the actual unfolding of the psychology of child nature" (Dewey, 1911, p. 241, cited in Gould, 1977, p. 151). Although psychological recapitulation had both staunch supporters and detractors at the beginning of the twentieth century, its biological basis was decisively discredited (Davidson, 1914; Garstang, 1922; Gould, 1977; Rasmussen, 1991). Since then, mainly in the work of Piaget, Kuhn, and the conceptual change movement, various remnants of the recapitulation argument have remained (Clement, 1982; Kuhn, 1962/1996, 1977; Nersessian, 1989; Piaget, 1970; Piaget & Garcia, 1989; Schecker, 1992).

Since recapitulation is a discredited theory, current usage of the word "recapitulation" in the educational setting tends to be somewhat misleading, as, presumably, the referent no longer is the same as it was originally. The central argument of the theory of recapitulation is that the analogy between ontogenesis and phylogenesis is not just a similarity but represents a causal connection between phylogeny and ontogeny that can be used in the explanation of development. Moreover, the theory claims that the individual passes through all stages of development through which the species has previously passed (Koffka, 1931, p. 46). In Goethe's words, "die Jugend muß … von vorn anfangen und als Individuum die Epochen der Weltkultur durchlaufen" or "young people must … start at the beginning and, as an individual, traverse the epochs of world culture" (in Schmidt, 1909, p. 156, S. Klassen, Trans.). Any contemporary use of the term "recapitulation" would presumably not contain these elements in its meaning. But, what do current theories mean by "recapitulation" and what alternative terminology is used to denote any similarities between individual development and history?

A more easily defensible theory, the *theory of correspondence*, was put forward by Koffka, who claimed that ontogenesis and phylogenesis show similarities because both depend on certain general characteristics of the individual's reaction to the environment (Koffka, 1931, p. 47). The theory of correspondence has the advantage of not being dependent on a particular theory of development, although it does assume that reactions to the environment, i.e., behaviour patterns, are fundamental rather than the environment itself. In this respect, the theory of correspondence anticipates Piaget's *genetic epistemology*. Koffka's theory, like Piaget's, tends to be developmental in nature, rather than behavioural.

Jean Piaget began his studies while biological recapitulation was waning in acceptance. He eventually accepted a moderate view somewhat similar to that espoused earlier by Koffka (Koffka, 1931; Piaget, 1970; Piaget & Garcia, 1989). Piaget expert, Robert Campbell, however, maintains that it took Piaget twenty years to disengage himself completely from acceptance of the arguments of recapitulation (Campbell, 2000). Piaget did not use the term "recapitulation" in his later work, but rather the term "genetic epistemology" to refer to the parallel between history and children's development (Piaget, 1970). Like Koffka before him, Piaget did not believe in a causal mechanism connecting ontogeny with phylogeny. Bärbel Inhelder makes this clear in her foreword to Piaget's and Garcia's *Psychogenesis and the History of Science* where she writes that

> the author's purpose in studying these generalized mechanisms was not to describe term–by–term correspondences [between science and childhood], and even less to propose a recapitulation of phylogenesis by ontogenesis, nor even to demonstrate the existence of analogies in sequencing. Instead, they wished to see if the mechanisms mediating the transition from one historical period to the next ... are analogous to those mediating transitions from one developmental stage to the next. (1989, p. x)

What is not clear, however, is whether one is to use children as a means of understanding history or history as a means of understanding children. There is some evidence in Piaget's writings for both views (Levine, 2000). Although it is clear in Piaget's writings that he used the history of science as a guide to understanding children's development of logico–mathematical thinking, he, nevertheless, expressed a preference to use children as a means of understanding scientists (adults). In his personal correspondence, he wrote, "J'ai peu travaillé en psychologie les rapports entre l'ontogenèse et la phylogenèse car, psychologiquement, l'enfant explique l'adult davantage que l'inverse" (letter of 21 Feb. 1972, cited in Gould, p. 426) or "I have done little work in psychology on the relationship between ontogenesis and phylogenesis because, *psychologically, the child explains the adult more than the reverse*" (S. Klassen, Trans., italics mine).

Thomas Kuhn, following Piaget, tended to use the analogy between children and the history of science for the purpose of constructing a particular view of the history of science. Kuhn wrote in 1977 that "part of what I know about how to ask questions of dead scientists has been learned by examining Piaget's interrogations of living children" (1977, p. 21). Not only does Kuhn use children's behaviour as an interpretive framework for historical science, but when the historical analysis becomes too difficult, he resorts to projecting children's behaviour on early scientists; for example, in *Essential Tension*, Kuhn argues that scientific novices learn new concepts by extending the set of exemplary solutions that have already been mastered. In the following passage, he asks the reader to bear with him in not using examples from the history of science to support his argument:

> Inevitably the latter [examples] prove excessively complex. Instead, I ask that you imagine a small child on a walk with his father in a zoological garden. The child has previously learned to recognize birds … . During the afternoon now at hand, he will learn for the first time to identify swans, geese, and ducks. Anyone who has taught a child under such circumstances knows that the primary pedagogic tool is ostension. (1977, p. 309)

What Kuhn means by "ostension" is the act of pointing to certain qualities of an object that will (presumably) create the ability to recognize all objects in that class. The fundamental assumption evident here is that early scientists and children both employ the same technique in mastering the concepts contained in their respective communities. However, Kuhn's use of the child–to–scientist analogy, in the above excerpt, differs from that used

1. Scientists, unlike children, master the most advanced levels of knowledge in their fields.
2. Scientists, unlike children, understand what they are investigating and the scientific methods used.
3. Scientists, unlike children, work within rigorous intellectual traditions.
4. The worlds of the ancient scientist and the modern child are incredibly different.
5. Ancient concepts are often invested with different meanings than they are today.
6. Scientists, unlike children, constitute a community committed to solving scientific problems.
7. Children have developmental constraints on their reasoning capabilities; scientists do not.
8. Level of language development is a barrier to the development of the number concept in children; in adults it is not.

Table 1: Differences Between Early Adult Scientists and Modern Naïve Students

by Piaget, who saw the passage through developmental stages as comprising the similarity rather than the particular learning heuristic.

There is evidence for the similarity of students' intuitive beliefs about the natural world and certain early scientific views. Similarities have been established in the areas of photosynthesis (Wandersee, 1985), elementary electromagnetism (Seroglou, Koumaras, & Tselfes, 1998), the relationship between force and acceleration (Clement, 1982), the relationship between force and motion (McCloskey & Kargon, 1988), projectile motion (McCloskey & Kargon, 1988), and elementary optics (Galili, 1996). McCloskey and Kargon have, however, noted that children's views of gravity are very different from those of early scientists (1988). One would not expect the similarities to be extensive,

1. Both early scientists and modern children are in a pre–paradigmatic stage.
2. Both early scientists and modern children are attempting to define theoretical entities and relate them in a rough theory.
3. Both early scientists and modern children are at the same level of scientific development, namely (2) above.

Table 2: Strauss' Reasons for Expecting Similarities Between Scientists and Children

owing to the great differences between early–stage adult scientists and modern naïve students.

Sidney Strauss lists eight major differences between the early scientists and children (Strauss, 1988, p. xvii). These are summarized in Table 1. As the Table shows, early scientists' and modern naïve students' thinking differ in the degree of sophistication of the knowledge considered. Other differences involve the social, intellectual, and technological context in which early scientists and modern naïve students acquire new knowledge. These contextual factors are radically different. Scientists, more than children, tend to be reflective about the methods they use, and their reasoning capabilities are more highly developed. Scientists, unlike children, constitute a community committed to the investigation of particular scientific problems. The world of early scientists was incredibly different, especially in terms of technological resources available for the investigation of phenomena.

In light of these major differences one would be hard pressed to rationalize the existence of a close connection between the thinking of scientists and children. Strauss, does, however, attempt to list similarities between scientists and children, as summarized in Table 2. It turns out that the similarities listed in the Table are all restatements of the developmental similarities between early scientists' and modern children's progress in acquiring new knowledge. Both early scientists and modern children are in the beginning stages of developing a new theory. As McCloskey and Kargon argue, both the early scientist and children are in the same developmental stage: children in the intuitive stage, and scientists in the pre–paradigmatic stage (McCloskey & Kargon, 1988). The developmental similarities can be justified by characterizing scientists' and children's theory development as the beginning efforts to move beyond a purely common–sense based novice understanding. That is to say, the theories have progressed beyond the stage of exclusively using entities that exist in the sensory world, but, rather, map everyday observations directly and simply onto theoretical entities. For example, motion as a result of a push could be associated with impetus; cooling or heating ("heat flow") could be associated with caloric; corpuscles could be associated with light rays.

Although there are several examples of the similarity of children's and early scientists views, the similarities cannot be generalized. There are many discarded scientific theories that children or science students will never develop on their own. In this respect, the neo–recapitulationist hypothesis breaks down in that it cannot be used to make predictions of children's views. Examples of theories that contemporary students, unlike scientists, have not intuitively developed are the Ptolemaic theory, phlogiston theory, and theory of the æther. If one considers the whole of the history of science, the number of examples of early scientific theories that are apparently adopted by students is small. There are thousands of published articles and numerous studies that deal with the preconceptions of students (Pfundt & Duit, 1994). However, only a handful of researchers have made the connection between observed preconceptions and historical scientific views (Clement, 1982; Gauld, 1998; McClosky & Kargon, 1988; Seroglou, Koumaris & Tselfes, 1998; Wandersee, 1985). In light of the preceding discussion, the neo–recapitulationist claim is difficult to defend and might, indeed, be more accurately characterized as a conjecture (Solomon, 1991; Solomon, Duveen, & Scot, 1992). Are the coincidences between early scientists' and students' views then to be taken as accidental? Nancy Nersessian takes a step back from this position, observing that both students and scientists are in a learning process (1989). However, until recently, the primary theoretical justification, the developmental claim, has been based on the Kuhnian paradigmatic model of the history of science. The paradigmatic analysis of history is hotly debated (Lauden, 1998; Levine, 2000; Scheffler, 1967; Toulmin, 1972), especially relating to the role of objectivity in science and to the manner in which theories replace one another, and, hence, the developmental explanation is on somewhat shaky ground as the main explanation for the scientist–children similarities.

The Pedagogical Argument

The attempts at establishing a scientific basis for linking history of science and science teaching, based on successors to the recapitulation theory, have gradually given way to attempts to establish a pedagogical basis for the linkage. Many of these attempts are based on particular views of what comprises learning. The dominant view, the conceptual change view, arose largely out of interpretations of Kuhn's *Structure of Scientific*

Revolutions. The most influential such attempt is the Conceptual Change Model (Duit & Treagust, 1998; Pintrich, Marx, & Boyle, 1993). Science educators and philosophers of science at Cornell University first presented the Conceptual Change Model in 1981 and 1982 (Hewson, 1981; Posner, Strike, Hewson, & Gertzog, 1982).

The Conceptual Change Model

The main presupposition of the Conceptual Change Model is that conceptual change in the individual is analogous to theory change in the history of science. Because the philosophy of science, as espoused by the philosophers like Kuhn, is concerned with the rationality of science, it serves as an ideal model for rational transitions in individual thought structures in science education. However, the Conceptual Change Model does not claim that the way in which scientists accept or reject new conceptions is the way in which individuals learn. Rather, it postulates some "structural features", like the nature of rationality, common between individual learning and scientific change (Strike & Posner, 1985). The Conceptual Change Model was not conceived as a theory of learning, but rather a philosophical framework for research into conceptual change (Strike & Posner, 1992). Because the Model is based on presuppositions about what should count as good reasons for rational conceptual revision it assumes a normative character. The term "conception" is preferred to "concept" (Strike & Posner, 1992) in order to imply the complexity of the cognitive structure involved. However, as some researchers have pointed out (diSessa & Sherrin, 1998), little attempt has been made in the Conceptual Change Model or other conceptual change models to define the term "concept" or "conception".

Thomas Kuhn's *The Structure of Scientific Revolutions*, first published in 1962, had a strong influence on the conceptual change movement, in general, (Duschl & Gitomer, 1991) and on the Conceptual Change Model, in particular. In Kuhn's account of the scientific enterprise, change must necessarily be revolutionary. The process of scientific change is the transition from what Kuhn calls "normal" science to what he calls "revolutionary" science. In normal science, scientists work within what Kuhn originally called a "paradigm" in his 1962 edition. Revolutionary change comes about when an increasing number of anomalous (unexpected and unexplained) results "pile up" in the paradigm. The paradigm first tries to assimilate these events by means of auxiliary hypotheses in its theory, some of which may be *ad hoc*. A time of crisis ensues, however, after which the foundations of the paradigm are called into question and new experiments and theories are proposed. Eventually, the scientific community will coalesce around some of these, ultimately bringing about a new paradigm. Later, in the postscript to Kuhn's 1969 edition of the cited work, he relaxed his notion of the paradigm and saw it as a disciplinary matrix. In Kuhn's modified notion, the paradigm consists of a) the theory, which has symbolic generalizations, b) metaphysical assumptions of the theory, c) scientific values, and d) exemplars, which consist of textbook or laboratory examples of concrete problem–solutions (Kuhn, 1996, 182–187). In his final formulation of scientific change, Kuhn modifies his view of revolutionary change and concedes that the characteristics of a paradigm (or disciplinary matrix) need "no longer to be discussed as though they were all of a piece" (Kuhn, 1996, p. 182). This concession allows for piecemeal change of paradigms over time so that not an entire set of commitments must be changed at once in a paradigm shift.

Paradigm shifts necessitate theory choices. Members of a particular scientific community have, according to Kuhn, a five–fold set of values that consist of a) accuracy, b) consistency (both internal and external), c) scope, d) simplicity, and d) fruitfulness (Kuhn, 1998). He claims that each paradigm has its own unique weighting of these values against which theories could be ranked within a particular paradigm. In this view, theory choice is a shared community decision, influenced by professional, social, and psychological factors, as well as the five–fold set of values (Nussbaum, 1989). Thus, theory choice is, at best, only partially rational.

The most controversial aspect of Kuhn's work is his notion of incommensurability. Scientists who are members of succeeding paradigms are sometimes unable to communicate with each other (Kuhn, 1996, pp. 148–150). They are no longer concerned about the same problems, their scientific values have shifted, and the meaning of terminology has changed. Consequently, members of a particular paradigm frequently find it very difficult to communicate meaningfully with the members of a preceding paradigm and vice versa. For example, members of the twentieth century physics paradigm talk about space, time, and motion in a way that would not easily be understood by members of the Newtonian paradigm. Problems that interest the twentieth century paradigm might be concerned with speeds approaching that of light, not a consideration for Newtonian physicists. Newtonian physicists would consider time and space as invariant and it would be very difficult for them to understand concepts like the relativity of simultaneity and length contraction. Critics have pointed out that that there are few examples such as these, and that generally, succeeding scientific paradigms have a sufficient overlap in content and meaning to be able to communicate, especially during the time of transition.

The developers of the Conceptual Change Model considered Kuhn's notion of incommensurability important to their Model. They use the term "perceptual categories" to designate incommensurable conceptions. Individuals who believe in the validity of incommensurable conceptions cannot come to agreement on the reasons to accept or reject one conception as opposed to another. In a similar fashion, because some conceptions fit into different "perceptual categories", it is difficult for adherents of a particular preconception to entertain conceptual revision towards an opposing perceptual category.

In the application of models of scientific change to learning theory, it is not clear whether these views reflect the real situation accurately. Especially problematic is the fact that its developers saw the Conceptual Change Model as a prescription for the kinds of things that ought to count in rational conceptual change. Kuhn's model, upon which their Model was based, however, is characterized by an element of non–rationality (incommensurability) in paradigmatic change in science. This makes it difficult, although not impossible, to justify the Conceptual Change Model on the basis of Kuhn's work (Michael Mathews, private communication, 2002). Furthermore, it is known that students do not change their entire set of beliefs at the time they accommodate a new view (Duschl & Gitomer, 1991) but it is not known at what rate or how radically such change takes place.

place. The uncertainties and debates over these issues in the philosophy of science are mirrored in the uncertainties and debates in learning theory. If, as is postulated here, philosophy of science has a significant influence on science learning theory, then the increasingly more inconclusive nature of the discussions in the philosophy of science may tend to add uncertainty to future discussions about learning theory.

Nevertheless, the Conceptual Change Model has reinforced the notion of learning as conceptual change. Claims were made that changes in historical scientific views can be used to help guide students to a scientific understanding (Monk & Osborne, 1997; Schecker, 1992; Stinner & Williams, 1993). There are a few research studies that indicate positive results in employing history of science to encourage student conceptual change (Seroglou, Koumaras, & Tselfes, 1998; Sneider & Ohadi, 1998; Wandersee, 1985). Although these initial studies are encouraging, they are not conclusive due to their small number and the absence of replication. What seems to be lacking from these studies is a theoretical framework dictating the method by which history of science material is constructed and by which it can be incorporated into instruction.

Providing a Meaningful Context for Learning Science

Another pedagogical argument for using history of science in instruction is that the science material to be taught must be situated in a suitable context. The contextual argument is not based explicitly on any particular model or theory of learning, nor is it based explicitly on contextualism as a school of thought. Rather, the contextual argument takes a common–sense approach to learning with the assumption that concepts taught in context will produce better learning outcomes than concepts taught in a decontextualized manner. In this sense, the contextual approach is implicitly based on moderate contextulism (Dembski, 1994). There is plausible evidence that teaching and learning methods imbedded in appropriate contexts are essential to engender meaningful learning (Cabrera, 1995; Martin & Brouwer, 1991; Roth & Roychoudhury, 1993). Historical contexts, when sensitively reconstructed, include a humanizing element, which may raise personal, ethical, sociological, and political concerns, which tend to engender increased motivation in students. The historical materials are not to consist of chronologies, but rather to expose the settings in which discoveries were made. German physics educator Walter Jung points out that "… educational value does not come from the details of the historical development of physics, but from the history of its context. This is as it should be: value arises from the richness of interrelations" (1994, p. 125). However, in reality, the contextual approach as the various advocates for history of science have described it has not yet been utilized in a substantial way. Instead, the typical curriculum, inherited from the 1960's and 1970's, as described by Canadian science educator Jacques Désautels, presents the material in a decontextualized fashion. Désautels, like many others, recommends the inclusion of history of science as a solution to the problem of decontextualization:

> By perpetuating overloaded curricula for years, often poorly suited to the intellectual development of the majority of students, the system has guaranteed that only a minority will eventually have access to scientific careers. By arranging curriculum content strictly according to logic and discipline, with no reference whatever to the history of science, apart from

> parenthetical anecdotes, it ensures that students do not absorb a critical view of knowledge. (Désautels, 1982, p. 53)

Although many issues today are different from those of the 1960's and 1970's, the concern that students develop a critical view of knowledge remains. Teaching science as a "rhetoric of conclusions" (Schwab, 1964, p. 24) does not encourage consideration of the origins of the science concepts and so does not allow for the learners' reflection on their philosophical presuppositions or the difficulties encountered by the developers of the concepts. The contexts in which those concepts were generated are social as well as scientific—contexts that can be "re–presented" only with an adequate knowledge of the history of science.

The proponents and practitioners of a contextual approach to the incorporation of history of science in science teaching have, generally, advocated a narrative approach to the presentation of historical material. Arthur Stinner, a strong advocate of the narrative approach to incorporating history, writes that "… learning could be well motivated by a context with one unifying central idea capable of capturing the students' imagination" (1992, p. 20). Various scholars have used the terms "narrative" (Kubli, 1998, Martin & Brouwer, 1991), "story" (Egan, 1989a; Keneally, 1989; Kubli, 1999; Stinner, 1995), "thematic" (Holbrow, Amato, Galvez, & Lloyd, 1995) or "storyline" (Arons, 1988; Coleman & Griffith, 1997; Stinner, 1998) to describe a number of contextual approaches. Generally, science educators have not made distinctions among the terms that describe the contextual approach, nor is there a consensus on the meaning of any of these terms; but, for the purposes of this review, it is desirable to see if a useful distinction can be made.

All of the contextual approaches listed above, whether story, storyline, or thematic, fall into the narrative category. In the broadest sense, narrative may be defined as "anything that tells a story, in whatever genre" (Jahn, 2001, par. N1.1) or "telling someone else that something happened" (Herrenstein–Smith, 1981, p. 228). Narrative is a rhetorical mode that has as its purpose the recounting of related events. Story, although it is a type of narrative, has a more restrictive meaning than narrative and might be defined as "a sequence of events and actions involving characters" (Jahn, 2001, par. N1.1). A key element considered by most story theorists as essential is the requirement that events of the story be chronological. A story must contain plot, which adds a causal or intentional element relating the incidents of the story (Egan, 1978; Prince, 1973). It is these elements of the narrative, and the story form in particular, that make it so well suited to the presentation of historical material. A major difference between recounting history and telling a story is the intentional element. However, skilful historical interpretation adds the element of motive to the narrative, thereby transforming it into a story. The thematic or storyline approaches are more difficult to characterize. Their advocates and practitioners only vaguely and generally describe the defining characteristics and it appears that no precise definitions for these approaches exist within the educational literature. The theme of a narrative is commonly thought of as the topic, proposition, or underlying idea that forms the basis or motivation for the narrative. Often the thematic approach will begin with a "big question" like "Why do we believe in atoms and their properties?" with the answer contained in a running presentation of related historical episodes. In this respect there does not appear to be a large difference from the storyline approach, which is based on "one unifying central idea that attracts the imagination of students" (Stinner & Williams, 1998, p. 1030). The term "storyline" is almost nowhere discussed by itself, although in common literary usage it refers to the sequence of related events comprising the story, devoid of the characters' motivations. Science education literature, however, seems not to distinguish between the words "thematic" and "storyline" when describing a narrative approach. Here the "unifying central idea" of the storyline is viewed essentially the same as the theme. Furthermore, the term "storyline" in science education can be used to describe either an instructional approach or a type of narrative structure. At best, one could formulate a definition for the *science* storyline, which lends itself to the use of history of science, as *a loosely–knit set of chronological episodes taken from the history of science, related either by the characters involved or the theme. These episodes provide coherence for the study of a topic.* The science storyline, however, is different from the literary storyline in that the literary storyline is the "skeleton" of a story whereas the science storyline is a collection of episodes that could *contain* stories which could stand on their own. The science story is a tightly–knit set of episodes that must be presented or read in one sitting whereas the science storyline is a loosely–knit set of episodes that may be presented or read in a series of sittings. Based on the usage of the term "storyline" by Holbrow, et. al. (1998), one must make the intentional element that is associated with "story" optional. Further comparisons and contrasts will be drawn between the two in Chapter 5 where the science story is discussed in greater detail.

Of particular note in the science storyline category of approaches is the Introductory University Physics Project (IUPP) which was launched in 1987 as an American effort to reform the subject matter and explore new methods of presentation for the calculus–based introductory physics course (Coleman, Holcomb, & Rigden, 1998). The project, which concluded in 1995, produced model curricula which were based on organizing themes which were called a "storyline". The project sought to decrease the number of topics taught, increase the coherence of the topics, and include more modern physics. However, none of the approaches explicitly utilized history of science and the results were disappointing in that they did not eliminate growing student disenchantment with physics and did not demonstrate improved student content knowledge when compared to the traditional approach (Coleman, Holcomb, & Rigden, 1998).

The narrative approach has a spectrum of possible applications, ranging from the smallest stand–alone story element like the vignette (Wandersee, 1992) or anecdote (Shrigley & Koballa, 1989), up to the largest story–like structure, the curriculum unit unified by a theme (Holbrow, Amato, Galvez, & Lloyd, 1995) or storyline (Coleman & Griffiths, 1997; Stinner & Williams, 1998). Of special interest here is the large context problem (LCP) as defined by Stinner (1985, 1990). The LCP seeks to present instructional concepts in contexts as close to eventual transfer situations as possible. The LCP belongs to the class of storyline approaches, but may employ other narrative techniques within its scope. For example, stories may be a part of the LCP in order to present the human side of the historical situation employed by the LCP. The historical situation, perhaps presented as a science storyline, gives rise to various interesting science problems to be considered and solved by students. Invariably, students find LCP's significantly more interesting and motivating than traditional lectures, cookbook–style labs, end–of chapter problems, or take–home assignments (Stinner, 1995). This conclusion is also attested to by an informal study based on a large context, which I have conducted at the University of Winnipeg and report on in Chapter 6. Other groups have applied the storyline or thematic approach in an even broader sense, using it to redesign an entire course. For example, Holbrow, Amato, Galvez, and Lloyd (1995) use the historical thematic approach for the organization of a first year physics course and its associated textbook, *Modern Introductory Physics* (Holbrow, Lloyd, & Amato, 1998). The textbook, while not a part of the IUPP initiative mentioned above, did embrace the IUPP principles implicitly. The text structures a course in introductory physics around the question "Why do we believe in atoms and their properties?" Its theme includes much of nineteenth and twentieth century physics and includes original sources, where appropriate. Holbrow, Amato, et al. (1995), report that student evaluations of the course improved with the new approach, as also did the retention rate of students from the beginning to the end of the course.

Providing Meaningful Activities for Learning Science

An effective way of teaching science is to have students "do science". Although some concepts and methods of current science are too advanced for students at the introductory level, historical science can, however, provide appropriate material for simpler concepts in science. This method, which might be called "historical recapitulation laboratories", has been advocated for some time and used with a moderate degree of success (Allchin, et al., 1999; Heering, 2000; Höttecke, 2000; Kipnis, 1996; Teichmann, 1991). Allchin, et al., (1999) found that students were not impressed primarily with the course content, but with the way in which it was presented, namely, by means of historical experiments. This observation is supported in a different setting by Ebenezer and Zoller (1993), who observe that teaching style appears to be a major determinant of high school students' attitudes toward science and science teaching. Furthermore, in Allchin's study, students' attitudes towards and understanding of science were shown to improve when using history–based laboratories, as compared to the usual lecture teaching techniques.

The historical recapitulation laboratory can also be integrated with the LCP approach. When students decide what problems to attempt, based on the historical case history, they may choose to redo various experiments that will aid in the overall investigation of the problems posed. The degree to which the experiments recapitulate their historical equivalents depends on the resources available. Students may read about the historical experiments and be given the opportunity to design their own experimental procedures in keeping with the historical record. I have used this method at the University of Winnipeg to allow students to design their own experiments to investigate Ohm's law and Coulomb's law. Students have exhibited enthusiasm for the approach that far surpasses their reaction to traditional labs and have expressed the desire to see more labs like these.

The Cultural Argument

Physicist Erwin Schrödinger wrote, in 1952, that "scientific findings … are meaningless outside their cultural context" (p. 3) and Ian Winchester defined this context when he stated that "… to contribute intelligently to the discussion of the place of science in civilization and culture, one requires a well–grounded picture of the past, including the scientific past" (1989, p. v). To develop a "culture" of science, in either the individual or societal sense, requires that attention be paid to the scientific heritage. This means that "an educated person should be aware of such a heritage in conceptual, historical, and intellectual terms, not in the mere assertion of end results" (1988, p. 15), according to Arnold Arons. The cultural dimension of science, which emphasizes the process rather that the product of science, has two directions: first, the intellectual development of the individual in understanding the richness of the role of science in his or her society, and second, the understanding of the operation and limitations of science in society for the purpose of democratic decision–making. However, as Neil Cossons, director of the Science Museum of London argues, the "informed citizenship" argument lacks both logical and psychological appeal for most people. Cossons argues that "citizenship in our culture is an ambiguous concept linked with politics—something to do with unwelcome burdens and responsibilities transferred from the state to the individual" (Cossons, 1996). Instead, Cossons crafts a new form of the cultural argument for understanding science:

> The distinguishing feature of modern western societies is science and technology. Science and technology are the most significant determinants in our culture. In order to decode our culture and enrich our participation—this includes protest and rejection—an appreciation or understanding of science is desirable. (Cossons, 1996)

Furthermore, the discourse of science–as–practised makes it inaccessible to the general public in a way not experienced by the humanities. This is where the history of science should enter—to portray science, "warts and all" as a human activity, an activity of people with aspirations, doubts, and difficulties as well as successes. The cultural aspects of science portray science as a human activity, true to the nature of science–as–practised.

Yet, the cultural aspects of science may be distinguished from nature of science considerations in this respect: the nature of science relates to the character of scientific investigation and the philosophical issues that are raised whereas the culture of science relates to the richness of the influence that science brings to the individual or to society.

The cultural aspect of science is closely related to the aims of scientific literacy discussed earlier. When viewed in this light, the cultural argument becomes a necessary argument, a kind of "cultural necessity". The supposition that history of science has value in communicating the culture of science, then, does not require empirical verification. It is a given in our culture. Carl Sagan expressed the critical importance of scientific awareness when he warned that "we are in real danger of having constructed a society fundamentally dependent on science and technology in which hardly anyone understands science and technology. This is a clear prescription for disaster" (1989, p. 295). The cultural argument for history of science in science education is likely fundamental, an underlying principle. If so, it need not be justified and it cannot be tested.

The Philosophical Argument

The arguments from the liberal view of education originated from the philosophical perspective in education that the individual, as opposed to society, is to be the primary beneficiary of a good education. Such an education must be one that is philosophically well–founded. Historian of science and mathematics, Otto Neugebauer, writing in 1951, saw a philosophically sound education as one founded in history. Neugebauer argued that "the main purpose of historical studies [is] in the unfolding of the stupendous wealth of phenomena which are connected with any phase of human history and thus to counteract the natural tendency toward oversimplification and philosophical ignorance" (1951/1969, p. 208). Today, the role of history in communicating an accurate picture of science or the nature of science is again prominent in the arguments of many of the proponents for history of science in science education (Brush, 1989; Irwin, 2000; Justi & Gilbert, 1999; Kragh, 1992; Lederman, 1998; Solomon, Duven, & Scot, 1992; Teichmann, 1991). Not only should the picture of science conveyed to students accurately reflect its origins and nature, but it should be presented in a way that is seen by the majority of students as relevant. Robert Carson contends that "science education will not seem relevant to most students until they are able to see it from the vantage point of humanity. That is, in addition to grasping science content conceptually they must experience deeply its historical, philosophical, cultural and social dimensions." (Carson, 1997, pp. 230–231). In order to accomplish this, the questions considered in the classroom must move beyond the "what" of science to the "why" and "how". And this approach is difficult to imagine without the inclusion and integration of philosophy and history of science in the teaching. In the context of education, the philosophy of science takes on a character more simplified than that implied by the current contentious discussions by philosophers of science about the nature of scientific rationality and change. Instead, philosophy in the context of the science classroom seeks to answer more practical questions about the nature of science.

Research has shown that incorporation of history of science into science instruction is effective in leading students to a better understanding of the nature of science (Brush, 1989; Irwin, 2000; Solomon, 1994). However, science educator, Norman Leder-

1. Scientific knowledge while durable, has a tentative character
2. Scientific knowledge relies heavily, but not entirely, on observation, experimental evidence, rational arguments, and scepticism
3. There is no one way to do science (therefore, there is no universal, step–by–step scientific method)
4. Science is an attempt to explain natural phenomena
5. Laws and theories serve different roles in science, therefore students should note that theories do not become laws even with additional evidence
6. People from all cultures contribute to science
7. New knowledge must be reported clearly and openly
8. Scientists require accurate record keeping, peer review and replicability
9. Observations are theory–laden
10. Scientists are creative
11. The history of science reveals both an evolutionary and revolutionary character
12. Science is part of social and cultural traditions
13. Science and technology impact each other
14. Scientific ideas are affected by their social and historical milieu

Table 3: Consensus Nature of Science Objectives (McComas, et. al., 1998)

man (1998) sounds a cautionary note, pointing out that not all studies of the effect of history of science on understanding the nature of science have positive results (for example, Abd–El–Khalick, 1998, cited in Lederman, 1998, shows little impact). Lederman (1998) points out that studies where the nature of science objectives have been made explicit in the instruction are the ones that have been more successful (for example, Jones, 1969; Ogunniyi, 1983; Olstad, 1969).

For those sympathetic to the objective of teaching the nature of science within science, deciding which assumptions about the nature of science are important is a challenge. As McComas, Almazroa, and Clough (1998) and others point out, there has been a characteristic lack of agreement on the tenets of the nature of science. However, in science education the objectives are not the same as they are in philosophy. Here the tenets are simpler and consensus is easier to achieve. Perhaps philosophers may not find agreement easy on these issues (Alters, 1997), but the science education standards documents, at least, show a high degree of consensus.

McComas, et al., (1998) have identified these consensus objectives and they are shown in Table 3. While students, especially in the higher years, might tend to agree with some of the tenets, they would find it difficult to find examples to support such opinions. Other tenets, especially number 5, are more problematic, with students almost invariably demonstrating confusion about the matter. It seems impossible for students to obtain an adequate understanding about these philosophical issues without being able to relate them to real illustrations in the history of science.

Progress in the Use of History of Science in Science Education

Science historian Stephen Brush, writing in 1989, observed that "we now have enough concrete evidence showing that the historical approach [in science teaching] does have an impact on students" (p. 66) and a decade later Lombardi noted that "there is practically unanimous consensus about the relevance of the history of science to the educational process" (1999, p. 217). These observations suggest that there may have been some progress towards reaching the goal of a greater prevalence of history of science in science education literature, but whether there has been progress in classroom implementation is arguable. A lack of progress in implementation has been attested to by Monk and Osborne, who argue that secondary science education is still in the same state it ever was in that there is still "continued special pleading, rather than confident endorsement for the place of history and philosophy of science ... in science teaching" (1997, p. 405). There may, however, be a greater degree of progress in university science curricula, as exemplified by the work of Holbrow and his collaborators at the Colgate University Physics Department (Holbrow, Amato, Galvez, & Lloyd, 1995).

The main argument for history of science in science teaching, according to Michael Matthews, is that it "promotes better science learning" (1989, p. 7). In the same journal issue, Brush adopts a somewhat defensive tone when he points out that there is evidence that the historical approach *does not interfere* with the "learning of the technical content of science" (1989, p. 66). A decade later, Irwin lamented the fact that the historical approach yielded "no difference in understanding of contemporary science content" (2000, p. 5). If history of science is to produce better science learning, it is small consolation that, at least, it does not interfere with the learning of science content. However, a recent study by Galili and Hazan is possibly the first to demonstrate a clear improvement in students' content understanding as a result of the generous incorporation of historical models into instruction (Galili & Hazan, 2000). Galili and Hazan's study, using the topic of optics, is marked by a clearly conceptualized theoretical background, unlike many other studies. The method is careful not to use the chronicles of discoveries, but rather to reveal the conceptual evolution of scientific thought about the topic studied. The authors have followed a structural view of student knowledge based on Jim Minstrell's theory describing preconceptions and conceptual change (Minstrell, 1982). Student concepts are organized into categories that take into account the various contexts in which they can appear—these are called facets of knowledge:

> Facets may represent consistently applied explanations manifested in a declarative knowledge, but not only. They can also express certain strategies, elements of students' characteristic behaviour (procedural knowledge), when coping with particular questions and problems. Facets are … context specific … [and] may incorporate several concepts, related in such a way as to represent individual comprehension of the situation. (Galili & Hazan, 2000, pp. S3–S4).

Students are pre–tested to reveal their facet–preconceptions in the areas to be taught. Instruction is customized to address conceptual weaknesses. A specialized textbook, compiled by Galili and Hazan and heavily incorporating the historical development of the relevant scientific concepts is used. It is possible that Galili's and Hazan's study represents a breakthrough in effectively applying the history of science method, although they caution that a follow–up study should be conducted to enhance validity.

Were it not for the one study of Galili and Hazan, the performance of historical approaches would be sorely disappointing in not producing better content understanding. Galili and Hazan's study is unique in integrating a theory of learning at each stage. Their approach is consistent with the recommendation of science educator Nancy Nersessian who suggests that history and philosophy of science and science education should interact through cognitive science (Nesessian, 1989). It appears that the lack of integration of the history of science approach with pedagogical theory along the lines suggested by Nesessian is a possible reason for there not being more successes to report. This hypothesis receives support from the observation that the lone study demonstrating improved conceptual understanding using a historical approach is also unique in having integrated a comprehensively formulated pedagogical theory both into instruction and into the study itself.

Chapter 3

FORMULATION OF THE RESEARCH APPROACH

A Statement of the Academic Research Problem

In the previous chapter it was argued that the effective and general use of history of science in teaching science has not been achieved to a significant degree, despite a sustained and supportable call for its use. Numerous attempts to integrate history of science into science teaching and curriculum have been made, along with even more numerous recommendations and justifications for doing so (for example, see Galili & Hazan, 2000; Irwin, 2000; Lombardi, 1999; Monk & Osborne, 1997; Stinner & Williams, 1998). There seems to be a consensus among many educators to integrate history into science instruction in some fashion; however, there is no agreement on a theoretical or methodological basis on which to proceed.

The lack of consensus should come as no surprise. Thomas Kuhn, referring to science research, observed in 1962 that "history suggests that the road to a firm research consensus is extraordinarily arduous" (1962/1996, p. 15). This statement could very well be extended, by analogy, to history of science in science education. Kuhn used the term "paradigm" in his ground–breaking work *The Structure of Scientific Revolutions* to refer to the "research consensus" among scientists. Similarly, there are difficulties in reaching a consensus in the emerging discipline of history in science education or in reaching the status of a paradigm. It may be that, if the proponents of history in science teaching recognized their field as being in a pre–paradigmatic state, they would be able to proceed without fearing that something was amiss in the field due to any so–called "failures" to sustain reform efforts.

The situation is not unlike that of the eighteenth–century investigation of electricity, described by Kuhn in his *Structure of Scientific Revolutions* in which he emphasizes that there were as many theories as electricians who practised in the field. He points out that "the basic problem here is a lack of 'progress': everybody [feels] the need to start over again from the basic principles" (1963, p. 362). Similarly, science educators find it necessary to justify, over and over again, their advocacy of history. This situation is a tell–tale sign that a research community is struggling to establish a viable theory. What has resulted is a reform by advocacy, a popular means of achieving goals in education that depends on the perseverance of the advocate of a particular methodology or approach and the support that he or she enjoys at any particular time. But when there is paradigmatic coalescence, reform by advocacy is no longer necessary. In his writing about the history of electricity, Kuhn maintains that from the time of Benjamin Franklin's theory, electricians saw the world differently (Kuhn, 1962/1996, pp. 111, 118). One way to achieve a "paradigmatic coalescence" of views on a particular theory is to develop a new or unifying theory with higher explanatory powers. A viable theoretical framework provides a basis for action in the form of guiding ideas that can provide not only the framework for implementation, but also the motivation.

Theoretical and Conceptual Research Approaches

Research and scholarship in education is dominated by empirical investigation and, arguably, this is as it should be. The model for many of these empirical investigations is well described by "the scientific method" as outlined by Conant (1951). Such activities of experimental scientists, as for educational researchers, may often be described, in Conant's words, by the following "method":

> (1) a problem is recognized and an objective formulated; (2) all the relevant information is collected (many hidden pitfalls lie in the word "relevant"!); (3) a working hypothesis is formulated; (4) deductions from the hypothesis are drawn; (5) the deductions are tested by actual trial; (6) depending on the outcome, the working hypothesis is accepted, modified, or discarded. (Conant, 1951, p. 50)

Conant qualifies his description by saying that only some scientific work proceeds along these lines. Paul Hurd, in a critique of educational research, raises a problem with the "method" in that "the whole idea of trying to pinpoint answers to questions that are raised in advance of a study produces results of little consequence" (1991, p. 726). The formulation of research questions in advance depends on the background theory that one initially adopts. It may be that questions may need to be changed in response to a dynamic, complex situation, as a study proceeds, since, as Paul Wachtel points out, "the answers one gets in research depend on the questions one asks" (1980, p. 407).

Learning theory, which is at the heart of educational theory, deals with extremely complex phenomena. Although education is about real students and teachers in real classroom situations, it is also about the mind, brain, physiology, and the particular social environment of the individual. These entities, for a large part, cannot be directly observed. The process of "learning", which is one such unobservable, must be evaluated by proxies, such as tests. However, as philosophers of science have shown, our observations are steeped in theoretical commitments, whether we are aware of them or not. It seems, then, that in order to make good sense of what we observe in education requires good theories and models about perceived phenomena that cannot be directly observed.

Theories in education are, in general, in a pre–paradigmic state (Hurd, 1991; Monk & Osborne, 1997) as I have also argued for the case of history of science in science education, and, therefore, the issues and questions themselves may need, eventually, to be revised. The tenuous character of research questions raises the importance of the dynamics of theory development in educational research. Educational theories are not just "out there"—they need to be developed. As University of Toronto philosopher Andre Kukla observes, "data do not yield up theories of themselves, nor will theories emerge by adding more data to the lot. There is no alternative but to invent a theory" (1989, p. 785).

The Development of a Theoretical Framework

Theories in education may be developed, enhanced, or tested in numerous ways. Kukla (1989) has written about theory development in the social sciences in detail and the categories in the following discussion are partly based on Kukla's categories of non–empirical issues in research and scholarship. Views on the meaning of theories in the sciences and social sciences are manifold and open to debate (Schwitzgebel, 1999; Ohlsson, 1999) and it is not my purpose to develop a definitive exposition of views on the meaning and development of models and theories. Instead, I will present a reasonably straightforward interpretation that can be used to guide the use of terminology later on. The term "theories" is used in many different senses, including its usage in everyday discourse. Hence, there is considerable value in clarifying what is meant by "theory" when it is used in the development of a theoretical framework in science education.

Theory Construction

The overall or main objective of non–empirical research and scholarship is theory development of various kinds. The task of theory *construction*, to use the term of Kukla, sometimes follows the observation of novel data or phenomena and attempts to explain them. A particularly good historical example of this is the series of explanatory triumphs of the Bohr atomic model in 1913. At that time, new spectral lines had been discovered in a mixture of hydrogen and helium that did not fit the Balmer formula. Not only was Bohr able to explain the result in terms of an ionized helium atom, but when, initially, his expanded theory did not agree exactly with more accurate experimental values, Bohr pointed out that he had not taken into account the finite mass of the nucleus. When he made that adjustment, agreement with measurements was exact. The considerable success of Bohr's model in explaining the newly–observed phenomenon resulted in a considerably greater degree of acceptance of his model in a short time. For example, when Einstein was told of Bohr's success, he is reported to have said "This is an *enormous achievement.* The theory of Bohr must then be right." (Fowler, 2002).

At other times, a theory may be constructed at least partly based on *a priori* reasoning or thought experiments, as in the case of Einstein's theory of relativity. Ian Winchester (1990) characterizes thought experiments as a "certain species of metaphysical argument or argument proceeding from our certainties of an ordinary kind about the world in which we live" (p. 74). A frequently–cited example of the thought experiment is Einstein's development of his special theory of relativity. Winchester explains how Einstein gave up certain everyday certainties and adopted others in arriving at his famous theory:

> Now when Einstein comes to frame an argument in his 1905 paper on special relativity, … which assumes the possibility of a fastest speed C, which he identifies with the speed of light, he gives up Leibniz's assumption of the dimensional permanence of bodies under any conditions of motion. … The reason he gives up the very natural assumption that the dimensions of a body are permanent, regardless of the state of motion of the body and for all observers is that he is in possession of another commonplace certainty, one that Newton and Leibniz would have considered commonplace too. This other certainty is that the laws of physics are independent of observers. They cannot be dependent on the state of motion of a particular object … and thus cannot be dependent on different observers. If they were, then instead of there being a few laws of physics there would be infinitely many. (p. 75)

Although Einstein and Lorentz were nominated for the Nobel Prize in 1912 by Wien, the 1911 Nobel winner, Einstein did not receive the prize for this work. Neither did Einstein spend any time seeking further experimental verification of special relativity. Rather, he carried on with different problems and left the problem of confirmation for others.

Theory construction can proceed along these two paths—from experiment to theory or from theory to experiment. However, any theory must assume that the known facts (observations) can be deduced from the theory in a way that is amenable to empirical testing. In this way, the theory takes into account Popper's (1963) necessary, but not sufficient, condition, that, in order for a theory to be scientific, it must be falsifiable. Popper was looking for daring predictions. In the case of Einstein's theory, for example, testing consisted, in part, of attempting to observe the bending of light rays in passing by a massive stellar object, surely a daring prediction.

In education, theories must also lend themselves to testing. For example, conceptual change theory makes the argument that much of the learning process involves the change of conceptions from inadequate, naïve forms to scientifically adequate forms. The testing of such theories depends on the existence of models suitable for incorporation into instruction where they can be tested for improved student learning.

Derivation of Empirical Consequences

Usually, however, theory development takes on a form more complex than is implied by the direct path of theory invention, model formulation, and testing described above. Once a theory is proposed, its empirical consequences need to be developed, over time. As the theory becomes better understood, new ways will emerge for testing that theory. New conceptual insights of the theory become apparent. These can be used for clarification and development of the theory. For example, models for incorporation of history of science in teaching may move beyond the objective of obtaining improved understanding of the nature of science to obtaining improved conceptual understanding. In so doing, models are opened up to new empirical tests. Good models are central to good theories in education, since they should not only result in sound instructional strategies, but they are vehicles for testing of the theories.

Conceptual Clarification

There is a pressing need for conceptual clarification in education, where cognitive theories abound. Moreover, the originators of educational theories and models have developed their own unique terminology. However, it may be that various theories and models have essentially the same referents, even though using different terms. The claims and conclusions of such theories may also overlap, to a large extent. There are a number of recent examples of conceptual clarification in educational theories. Rowlands, Graham, and Berry (1999) criticize the variants of conceptual change theory, noting contradictions among various conclusions that supposedly describe the same learning processes. Peter Slezak criticises cognitive and constructivist learning theories for "their obscurantism and jargon–laden trivialities" (2001). Peter Machamer and Lisa Osbeck (2001) examine what the literature means by "active" learning, pointing out the daunting complexities of the processes involved, and exploring what would be involved in constructing a meta–model (a model about models) of cognitive processes in active learning. In this way, sound criticism is an important method by which to keep theory developers accountable to the education community at large.

An aspect of theories that is not always explicitly stated is their presuppositions (Collingwood, 1945). According to Collingwood, presuppositions are basic assumptions that one makes in a discipline that are empirically not testable. Such assumptions may be implicitly held and not be obvious until subjected to the scrutiny of critical analysis. Ideally, theory development should begin with the outright consideration and statement of fundamental assumptions or presuppositions. Then, testing may take place after the eventual formulation of empirical consequences, thereby avoiding being questioned on validity due to ambiguity about the grounds upon which the theory is based. For example, the basic assumptions in conceptual change theory are that learning is a process of conceptual revolutions and that children learn science like early scientists. Criticism might legitimately question these assumptions (Levine, 2000).

Conceptual Innovation and Model Building

One way of viewing theory development is as a process beginning with conceptual schemes that progress to making analogies, then constructing models to become part of the theory (Dilworth, 1990; Harré, 1970). Much of this development is a task of creativity and inspiration. At this early stage, theories may not be mature enough to be submitted to rigorous testing and are commonly called proto–theories. In characterizing theories at any stage, one must bear in mind their overall purpose. In science, it is generally accepted that theories provide explanations of phenomena (Dilworth, 1990; Harré, 1970; Markovsky, 1997). In science education, theories are often preceded by foundational questions, like "What does it mean to learn?". The answers to such fundamental questions are important. It could be argued that conceptual change theorists, by not seriously re–examining fundamental assumptions such as recapitulation, have tended to beg the question on the issue of what it means to learn. Even though they are sometimes overlooked, foundational questions are much like requirements for explanation and a reconstruction of such questions for existing theories would be useful. Conceptual schemes and models, which are parts of the construction process of theories, support the attempt to provide explanations. In the case of the conceptual change model an analogy is made between children and historical scientists. The conceptual change model claims that the development of concepts in science can serve as a representation of the learning process of children. Models could, then, in the most general sense, be described as representations of the "problematic" in terms of the familiar (Dilworth, 1990). Problematic concepts or phenomena, in the context of theory development, are those that require explanation in some significant sense. In our running example, according to conceptual change theory, the nature of children's learning is a problematic concept that is described by some variant of the recapitulation model. In order to represent problematic phenomena, models often, but not exclusively, rely on analogies, as in the case of conceptual change. Conceptual schemes, on the other hand, do not seek to represent the unfamiliar in terms of the familiar. Instead, they seek to bring to bear major insights or organizational principles that will clarify theory development.

An example of an organizational scheme is Stinner's (1995) LEP "model", which is more properly classified as a conceptual scheme. The "model" relates the logical, evidential, and psychological aspects of learning in a way that facilitates the construction of lessons based on sound pedagogical principles. It does not employ an analogical model. For the purpose of this study, I will define a conceptual scheme as *an organizational approach to problematic situations for the purpose of clarifying theory development*. Stinner's LEP model, which is discussed in greater detail below, fits the definition of a conceptual scheme in that it relates various aspects of learning in an insightful way so as to overcome the traditional dry textbook–centred approach to teaching.

Standards for Theory Development

Theory development proceeds according to various objectives and in various possible stages, as described above. And even though theories must ultimately be subjected to empirical testing, their development always proceeds on a creative basis (Dilworth, 1990; Kukla, 1989). On the other hand, the developers or critics of theories must bear in mind certain standards of rigour and rationality that lend credence to the whole exercise of theory development. Beyond needing to be based on clearly understood presuppositions, theories must be exclusive in the claims that their developers seek to establish—that is, they must deal with a clearly delimited class of issues or phenomena. Indeed, in order to be considered scientific in any sense, theories in education must meet a number of standards of rigour. Barry Markovsky (1996) of the University of Iowa has argued that there are at least eight necessary standards for theories. He maintains that theoretical statements must be free of contradiction, free of ambivalence, communicable, abstract, general, precise, parsimonious, and conditional (p. 33). His remarks, based on Cohen (1989), bear repeating here.

> (1) A theory containing a contradiction loses all explanatory power because any such argument is always logically false, whatever its content.
>
> (2) Ambivalent statements such as "gender may affect attitudes" are ineffectual in theories because they are always logically true, regardless of content.
>
> (3) Communicability requires theories to be accessible to interested others—adherents and skeptics alike—so that they can understand the theory well enough to submit it to stringent tests.
>
> (4) Abstractness is the quality of not being bound to specific objects, times and places. Theories help to explain particulars, but also must transcend them. Abstract theories often contain terms unlike any used in everyday

> discourse. Though perhaps counterintuitive to some, this can be a great asset when the terms are well–chosen and sharply defined insofar as theories are supposed to provide insights which go beyond everyday points of view and familiar empirical instances.
>
> (5) Theories are general to the extent that their statements are both interpretable and corroborated for a large number and variety of cases. The criterion of abstractness does not anchor the theory in empirical reality; the criterion of generality does. Interpretability thus requires the terms of the theory to be connected to many and varied empirical instances, whereas corroboration requires that the theoretical assertions built from those terms are verified through observation.
>
> (6) Theories are precise to the degree that they generate accurate and detailed statements about phenomena.
>
> (7) The criterion of parsimony demands that, all else being equal, smaller theories are preferred to larger ones. If Theory A can generate the same hypotheses as Theory B while employing fewer terms and fewer assumptions, then Theory A is preferred. Parsimony facilitates communicability and provides greater opportunity to explore logical entailments.
>
> (8) Finally, Cohen (1989) cites three ways that theories are conditional: (i) They contain chains of logically related conditional statements that predicate the state or level of one concept on that of another. Without these types of statements there is nothing to test. (ii) Initial conditions employ definitions of terms to bridge the theoretical and empirical realms, allowing us to derive hypotheses about real–world phenomena. (iii) Scope statements formulate domains within which hypotheses may be tested. Without them, a theorist is either deceiving herself or trying to deceive others as to the true generality of his or her theory. (Markovsky, 1996, p. 34)

These eight standards need to be kept in mind for any theory–builder or critic. What they provide for theories is a standard for "testing" of a theory that precedes empirical testing. In this scheme of theory development, formal empirical testing is only one stage of development at the point that the theory is mature. However, since educational theories often deal with instructional techniques, they will be implemented on an informal experimental basis where they yield anecdotal support. Finally, theories might never be tested by classical statistical means when they apply to small populations such as senior university classes.

Foundational Questions

As I have argued above, research questions evolve along with theory development. At the outset of this project the purpose was envisioned as the development of a theoretical framework for the inclusion of historical stories in university science instruction. As the research proceeded, it became obvious that not only was there a need for such a framework, but, in a more specific sense, for a schema by which such stories could be integrated with a suitable instructional vehicle. The research question was then reformulated as follows:

1. *What contextual model of instruction at the middle or upper university level lends itself to effective teaching and significant learning?*

2. *What model of story accurately reflects major aspects of narrative theory and captures the essential features that make it an effective teaching device?*

Foundational Assumptions

As was documented and discussed in the proceeding chapter, many justifications have been brought forward for incorporating history of science and considerable support for doing so has developed. If the field of history of science in science education is to move beyond its pre–paradigmatic stage, then the desirability of the appropriate use of the historical approach must be taken for granted, and that will be done here.

Delimitation

Theoretical studies must, as was argued earlier, delimit their range of applicability in order to be considered testable. *The model of instruction developed here is deemed to be most applicable at middle or upper level university science.*

The Contextual Approach

The basic assumption about teaching and learning that will be adopted by this study is that a contextual approach is both desirable and beneficial in designing effective teaching strategies. Throughout the previous sections, the contextual nature of historical approaches has served as one of the main arguments to justify historical inclusion. And so, a delineation of what is meant in this study by a contextual approach and how it should be basically constituted is a reasonable first step in the development of a theoretical framework.

The process of endeavouring to learn can be viewed as an attempt to find appropriate and desirable contexts into which to fit new knowledge. Psychologist Barbara Rogoff describes context as "the integral aspect of cognitive events" (1984), so that cognition and context are inseparable. The current view of cognitive psychology about the importance of context is strongly expressed by Ryan Tweney when he writes that, importance of context is strongly expressed by Ryan Tweney when he writes that, "cognition is contextually dependent and must be described in that context before it is understood at all" (1992). But what does the word "context" convey in the science–educational setting? Baker, O'Neil, and Linn explain two different usages of the word "context":

> … the term *context* has different and somewhat conflicting meanings. Some proponents use context to denote domain specificity. Performance in this context would presumably show deep expertise. On the other hand, context has been used to signal tasks with authenticity for the learner. The adjective *authentic* is used to denote … tasks that contain true–to–life problems or that embed … skills in applied contexts. (1994, p. 335)

Baker, et al., see the knowledge–centred and the activity–centred contexts as somehow incompatible. But in the constructivist view, knowledge development proceeds as an activity of the learner. Hence, the argument can be made that the two meanings of context are not contradictory, but rather complementary (Koul & Dana, 1997; Rogoff, 1984) This is also born out in research reported by Ebenezer and Gaskell (1995) who draw on the insight of Marton (1981) when they write that

> … we often find variation in conceptions not only between children but also within the same individual. Depending on the context, children may exhibit qualitatively different conceptions of the very same phenomenon. Thus meanings are context dependent. Conceptions are, therefore, not characteristics of an individual, rather they are characteristics of the relations between an individual, content, and context. Learning is both context and content dependent. (Ebenezer & Gaskell, 1995, p. 2)

Baker, O'Neil, and Linn's dual meaning of context—domain–specific and authentic—correlate with Ebenezer and Gaskell's "content" and "context". The domain–specific context relates to disciplinary knowledge that the learner wishes to acquire, and the true–to–life context relates to the learner's use of practical abilities in the process of acquiring that knowledge.

In considering context it would be useful to construct a working definition to guide further considerations. The word *context* originates from the Latin *contextus*, denoting the connection of words or coherence (Merriam–Webster, 2001). Originally, "context" was used, in the linguistic sense, to mean "the parts of a discourse that surround a word or passage and can throw light on its meaning" (Merriam–Webster, 2001). Often the words "environment" and "setting" are used as synonyms for context. Using the meanings and connotations of "context", "environment", and "setting", I propose a definition of "context" as *the entities that connect to or surround a focal entity and contribute to the meaningfulness of the whole.* The "focal entity" in the formal definition would be either a scientific understanding or ability, either a concept or skill. Meaningfulness then arises out of factors like familiarity, social interaction, activity, reflection, logical relation, emotional response, and so on, and in the sense of the definition these constitute a context for a concept or skill.

Contexts that are Important to Science Learning

The contexts relevant to learning could be viewed either from the perspective of the curriculum and the teacher or from the perspective of the student—originating either with the knowledge being taught or with the way students learn that knowledge. The scientific knowledge being taught may be broken into theoretical and experimental components, or, at a simpler level, into logical and practical components, in the same way that scientific research breaks into two separate, but complementary, streams. From the point of view of the student, "science in context illuminates the theoretical practices of science"

(Koul & Dana, 1997, p. 132) and furthermore, having the opportunity for hands–on science investigation will help guard against "giv[ing] up science before it starts getting interesting" (Koul & Dana, 1997, p. 132). Arthur Stinner has characterized the theoretical and experimental as the logical and evidential aspects of teaching, two components of his LEP or "Logical–Evidential–Psychological" model of teaching and learning (Stinner, 1992, 1995). The LEP model was developed primarily to address the problem of textbook–centred science education.

The LEP Model

Stinner (1995) and others (Martin & Brouwer, 1991; Monk & Osborne, 1997) argue that a central problem in science education arises from the dominance of the textbook in teaching. Thomas Kuhn, in describing his "normal science," pointed out the centrality of textbook "exemplars" in producing competent scientists. Kuhn argued that "doing problems is learning consequential things about nature" (1996, p. 188). Stinner (1992, 1995) takes a different view of problem–solving, pointing out that for many students "doing problems means memorizing scientific facts and practicing algorithms" (Stinner, 1995, p. 281). Textbook–centred science learning has come close to being a "verbal behaviour one emits to a stimulus", to use the phrase of Strike and Posner (1985, p. 212). Monk and Osborne (1997) characterize textbooks as providing "popular, contemporary, cleaned–up and prejustified accounts of the behaviour of the natural world" (p. 405–406). As Monk and Osborne see it, textbooks have not changed significantly in their sterile approach to science.

Textbook science is mainly concerned with the "logical plane of activity" in science. The logical plane of activity contains the finished conceptual products of science, which are laws, principles, models, theories, and facts (Stinner, 1995). Items on the logical plane do not produce genuine learning without being connected to the "evidential plane of activity". The evidential plane of activity contains the experimental, intuitive, and experiential connections that support the entities on the logical plane (Stinner, 1995). Making productive connections between the logical and evidential plane results in meaningful learning taking place. However, in order to connect the logical and evidential plane, one must pass through the "psychological plane of activity". The psychological plane of activity contains students' preconceptions and previous school science (Stinner, 1995). See Figure 2 for a representation of the LEP model.

The Social Element

The *process* of learning contains a number of important contextual factors or influences. Many psychologists and educators have pointed out the importance of the social element in promoting learning. Especially influential in advocating the positive social influence on learning is the Russian psychologist Lev Vygotsky (1978) who developed a cognitive theory of learning, before his premature death in 1934, that postulates a social context of varying strength that facilitates learning, which he called the zone of proximal development. According to Vygotsky, students, when they operate within their "zone of proximal development", facilitate the learning of concepts and the solving

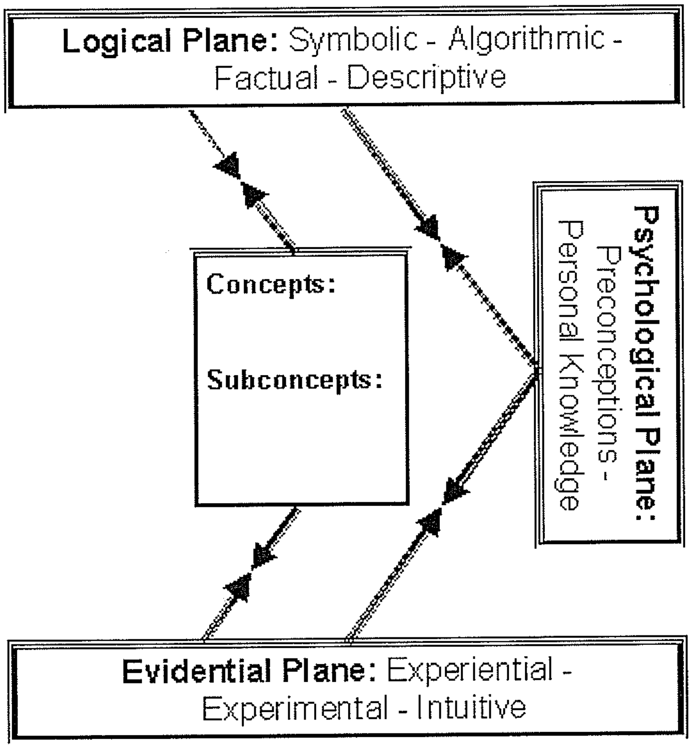


Figure 2: Stinner's (1995) LEP Model

of problems in a particularly efficient manner. Canadian science educator Jeffrey Bloom (1992) compares the manner in which students learn science in groups to the manner in which scientists "do science". In both situations, common beliefs of the social group contribute to its cohesiveness. The resulting social structure reinforces the development of a "school science" or Kuhn's "normal science", as the case may be, where anomalies or contradictions can place stresses on either the school or professional scientific social structure by introducing divergent views.

School Science and the History of Science

When concepts being considered are not at the forefront of research, but rather, a part of "school science", then the historical background becomes an important factor, as has been pointed out by numerous educators (Matthews, 1994; Monk & Osborne, 1997; Stinner, 1995; Stinner & Williams, 1998, Winchester, 1989). School science, unlike professional science, tends to be curriculum–dominated and textbook–centred. This is one of the main reasons that students tend to see science as "boring" or irrelevant. School science lacks the vitality of investigation, discovery, and creative invention that often accompanies science–in–the–making. For these motivational reasons and for the scientific, pedagogical, cultural, and philosophical reasons outlined in Chapter 2, it is desirable to integrate the historical element into science teaching. Indeed, the desirability of the appropriate use of the historical approach must be taken for granted. The humanizing and clarifying influence of history of science brings the science to life and enables the student to construct relationships that would have been impossible in the old decontextualized manner in which science was taught (Cohen, 1993; Jung, 1994; Kipnis, 1996; Koul & Dana, 1997).

The Narrative Element

Many researchers see the emotional or affective response of students as important to stimulate the learning process (Bloom, 1992; Bruner, 1996; Egan, 1986; Martin & Brouwer 1991). Bloom observes that student emotions colour their interpretation of concepts and that, moreover, "emotions, from a contextual point of view, can trigger specific

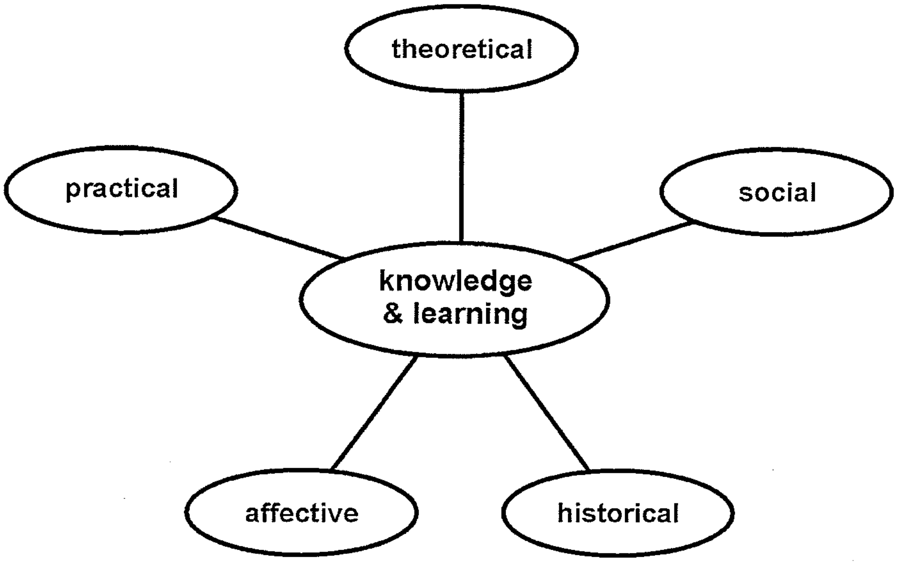


Figure 3: Five Important Contexts of Learning Science

meanings" (1992, p. 181). Educator Kieren Egan has related the emotional component in learning to the use of narratives in teaching (1986, 1989a, 1989b). Egan claims that the primary element in narratives that make them powerful teaching devices is their ability to stimulate an affective response in the reader or hearer.

The Relevant Contexts

Of the specialized contexts mentioned, each has been put forward almost singularly by the indicated science educator, philosopher, or psychologist. The complexity of contexts suggests that there are at least five distinct contexts of science learning. As I have implied, they are the 1) practical, 2) theoretical, 3) social, 4) historical, and 5) affective contexts. See Figure 3 for my representation of these contexts and their origin from the knowledge to be learned and the learning process. It is possible and, indeed, desirable for learning to take place in more than one context at a time; for example, a class may operate in both a historical and social context in the case of a group re–enactment of a historical science case study. I will argue in the next chapter that the "large context problem" in its proper implementation, as outlined by Stinner and modified by me, makes use of all five contexts.

Chapter 4

A THEORETICAL FRAMEWORK FOR THE CONTEXTUAL APPROACH

It is more than three decades since the large context problem approach (LCPA) emerged in science instruction. Arthur Stinner, its main proponent, advocated the LCPA as early as 1973. The general approach was probably originated, in contemporary times, by Gerard K. O'Neill at Princeton in 1969 when he taught an introductory physics class and used problems relating to the newly–developing space–race. O'Neill published his famous paper on colonizing space (O'Neill, 1974) as a result of having taught this class. Stinner's approach was developed independently in response to his discovery that "tremendous motivation for learning could be produced by a context with one unifying, central idea capable of capturing the students' imagination" (Stinner, 1985, pp. 391–392). The LCPA, as it was originally conceptualized by Stinner, captures and formalizes elements of instruction utilized in senior high schools by the most capable teachers who realize that in order to teach more effectively they must move beyond the dry approach dictated by the textbooks. To gain this objective, they must seek to eliminate "the gulf between scientific knowledge and 'common sense' beliefs" (Stinner, 1995, p. 555) that has branded school science as hopelessly boring and sometimes impossible to understand in the eyes of students. In designing a theoretical structure for the LCPA Stinner has based his model of the Large Context Problem (LCP) on his conceptualization of the nature of scientific thinking. The guiding assumption is that any sound method of teaching science must be based on a sound picture of science. The elements of design of the LCP must therefore correspond to elements of scientific enquiry viewed from a suitable philosophical and historical perspective. Five such elements, called "contexts of inquiry" by Stinner, are 1) the foundational questions that guide science, 2) the various methods by which science proceeds, 3) the paradigmatic problems of science (*a la* Kuhn), 4) the justifying experiments of science, and 5) the history of science that encourages students to view scientific developments in the context of their origin and justification.

The *context of questions* characterizes scientific inquiry, and after the notion of Collingwood (1945), maintains that a scientific fact is the answer to a scientific question. At the deepest level, answers to the questions in a particular area of science comprise its presuppositional structure. At the most superficial level, answers to questions support the Kuhnian activity of normal science by defining a range of problem–types that theory is particularly good at solving. Stinner's LCP seeks to encourage students to consider some of the more fundamental questions of science and engage in what he calls "high–grade thinking" (1985, p. 402).

The *context of method* characterizes the methods of science in a manner based on current thought on the nature of science. The methods of scientific investigation range from inductive through deductive approaches to creative endeavours. Students should, through being encouraged to ask probing questions about the procedures of scientists, develop a more realistic picture of the methods by which science operates.

The *context of problems* addresses the role of problem–solving in the mastering of a scientific discipline such as physics. Kuhn (1962/1996) argued that solving a large number of exemplars tends to lead students to a greater degree of understanding of the underlying laws. This also appears to be the view held by traditional teaching approaches. On the other hand, emphasis on problem–solving tends to encourage the memorization of algorithmic procedures and thereby discourage the development of understanding of the underlying concepts. Stinner (1985, p. 405) refers to these problems as "type problems" and he contrasts them to "contextual problems" that encourage the student to demonstrate depth of understanding and imagination.

The *context of experiments* is concerned with the classification of experiments in a spectrum from "cookbook labs" to research projects and thought experiments. The LCPA is designed to encourage the student to take on higher level experiments so that the student activities become closer to, though not identical to, the activities of practising scientists.

The *context of history* is designed to provide a sense of the development of scientific concepts in a way that is true to the historical account. This approach seeks to instil in the student an appreciation of the struggles, confrontations, and triumphs involved in "science–as–practised". Kuhn's exemplars or "type problems" are used, but also placed in history.

1. Map out a context with one unifying central idea that is deemed important in science *and* is likely to capture the imagination of the student.
2. Provide the student with experiences that can be related to his/her everyday world as well as being simply and effectively explained by scientists' science but *at a level that "makes sense" to the student.*
3. Invent a "story line" (may be historical) that will dramatize and highlight the main idea. *Identify an important event associated with a person or persons and find binary opposites, or conflicting characters or events* (Egan, 1986) that may be appropriate to include in the story.
4. Ensure that the major ideas, concepts and problems of the topic are generated by the context *naturally;* that it will *include* those the student would learn piece–meal in a conventional textbook approach.
5. Secure the path from *romance to precision to generalization* (Whitehead, 1985). This is best accomplished by showing the student that
    a. problem situations come out of the context and are intrinsically interesting;
    b. that concepts are *diversely connected*, within the setting of the story *as well as* with present–day science and technology;
    c. there is room for individual extension and generalization of ideas, problems and conclusions.
6. Map out and design the context, ideally in cooperation with students, where you as the teacher assume the role of the *research–leader* and the student becomes part of an on–going research program.
7. Resolve the conflict that was generated by the context and find connections between the ideas and concepts discussed with the corresponding ones of today.

Table 4: Guidelines for Designing LCP's (Stinner, et al., 2001).

Although the LCPA is designed to expose the complex interplay between theory and justification, it must also take into account the nature of the cognitive apparatus of the student, especially the situated nature of cognition. Hence, the LCPA seeks to establish diverse connections of scientific concepts to everyday phenomena, to "hands–on" experiments (experiences), and to various other concepts of school science. It is assumed that this approach will heighten the students' sense of familiarity with the material and tend to make the students more comfortable with their studies. Furthermore, the LCPA utilizes a "storyline" which I have called a science storyline, a running narrative, which imposes coherence, engages the students, and contributes to the memorability of the setting. The "major ideas, concepts and problems of the topic are generated by the context naturally" (Stinner, 1995, p. 562). The major feature of this approach is that it assembles topics that would normally be taught piecemeal at different places in the course and teaches them together in a natural relationship.

In designing an LCP teachers are encouraged to follow a seven–element process summarized in Table 4 (Stinner, et al., 2001). These seven aspects of preparing a LCP should not be taken as "seven steps" played out in sequence, but rather seven principles that will guide the LCP development. It is expected, that as the science storyline is developed, the central idea and related experiences may need to be adjusted and that when Whitehead's (1985) learning cycle is considered all four preceding aspects may need to be adjusted. However, it is only after the LCP has been developed to the extent of satisfying the first five principles that students may be involved.

Whitehead's Learning Cycle

In the early twentieth century, philosopher Alfred North Whitehead advanced a theory of education relevant to the liberal view on education and to much of educational development today. Whitehead's approach was motivated by his observation of the thought–deadening and motivation–sapping nature of the currently–dominant decontextualized methodology in education. The ideas taught in isolation he called "inert ideas". He concluded that "education with inert ideas is not only useless: it is above all things, harmful—*Corruptio, optimi, pessima*" (1929, p. 2)—the corruption of the best is the worst of all.

The cause for the situation, Whitehead took as a basic misunderstanding of the duality between education for personal interest and education for the disciplined acquisition of ordered facts. The dominant educational approach pursues its goal of disciplined acquisition of facts through the almost total dependence on textbooks. Whitehead maintained that "the drop from the divine wisdom, which was the goal of the ancients, to text–book knowledge of the subjects, which is achieved by the moderns, marks an educational failure, sustained through the ages" (1929, p. 45). Furthermore, "so long as we see intellectual education as merely consisting in the acquirement of mechanical mental aptitudes, and of formulated statements of useful truths, there can be no progress; though there will be much activity, amid aimless re–arrangement of syllabuses, in the fruitless endeavour to dodge the inevitable lack of time" (pp. 45–46). What the traditional approach does not realize is that "there can be no mental development without interest. Interest is the *sine qua non* for attention and apprehension" (p. 48). The solution is for education to marry methods to produce factual knowledge to methods to cater to personal interest.

Whitehead argued that personal interest and academic discipline must always operate together in a tension or duality, one constantly giving way to the other. This apparently dual cycle is actually a threefold cycle, as personal interest, a "free" or relatively undisciplined activity, gives way to disciplined learning, which gives way to insightful application, again a personally–motivated, but now a research–like activity. Ideally, this cycle can be described in the words of G. B. Shaw as a situation "in which work is play and play is life" (Whitehead, 1929, p. 67). Motivated, undisciplined learning is seen as a kind of "play"; disciplined learning, a kind of "work"; and ultimate application of the learned principles as "life".

The three–fold cycle of learning, Whitehead maintained, dominates all of learning, from hour to hour and from developmental stage of life to developmental stage of life. The first stage is the stage of *romance*. In this stage, "the subject matter has the vividness of novelty; it holds within itself unexplored connexions with possibilities half–disclosed by glimpses and half–concealed by the wealth of material" (p. 28). The next stage is that of *precision*, the mainstay of the currently–dominant practice of education. This stage "proceeds by forcing on the students' acceptance a given way of analysing the facts, bit by bit" (p. 29). The final stage is that of generalization, a kind of return to romance "but with added advantage of classified ideas and relevant technique" (p. 30). In this last stage, diverse connections are made between what has been learned and other disciplines or between what has been learned and practical applications.

Although Whitehead maintains that all education should be characterized by the repetition of this cycle, he warns that there is danger in exaggerating the separation and distinction of the phases. Instead, the cycle comprises an undercurrent that propels learning activities in one direction or another. Whitehead's philosophy of education is taken as a basis for Stinner's LCPA.

A Similar LCP Approach

Gil–Pérez and Carrascosa–Alis (1994) have independently developed a perspective on the LCPA, similar to that of Stinner. They argue that, based on the constructivist approach, knowledge construction must be associated with questions or problems. In maintaining that knowledge acquisition is motivated more by students answering questions than by them changing existing views, they break ranks with the conceptual change movement. In an earlier paper (1990) Gil–Pérez and Carrascosa–Alis showed how science methodologies, as well as scientific concepts, have changed in the history of science. If the metaphor of science students as scientists is to be applied consistently, students must develop skill in sound methods of science that go beyond the "method of superficiality" (Gil–Pérez & Carrascosa–Alis, p. 534). Hence, the students' common sense preconceptions, which often correspond to preclassical scientific conceptions, must undergo not only a conceptual change but also a methodological change. The conceptual change model, which seeks to change student conceptions, is inadequate in this sense. Furthermore, scientists come to their own knowledge not by constantly challenging their held beliefs, but rather by investigating problematic situations. This aspect of real science is also not taken into account by the conceptual change model. Along these lines Gil–Pérez and Carrascosa–Alis argue that teachers should "organize learning as problematic situations that pupils can identify as worth thinking about" (Gill–Pérez & Carrascosa–Alis, 1994, p. 307). They employ an analogy that views students as novice researchers who tackle open–ended and interesting problems in small groups.

The Nature of School Science

The common observation of science educators that the textbook is the dominant influence in most of classroom teaching is born out by the TIMSS survey (Schmidt, et al., 1998). The serious shortcoming of the textbook–centred nature of most of science education served as the primary motivation for Stinner's original inception of the LCPA. In his conclusion about the overuse of textbooks, Stinner is in agreement with many others, including, Whitehead (1929), Siegel (1990), Monk and Osborne (1997), and Van Berkel, et al. (2000). Van Berkel, et al., (2000) call Kuhn's description of the dominant methodology in science education *normal science education.* Interestingly, most of the above listed scholars would essentially agree with Thomas Kuhn's (1963) characterization of science education but not with his conclusions that "normal science" education is a necessary requirement for the successful production of scientists. Most of Kuhn's critics, in this regard, would agree with the earlier assessment of Whitehead (1929) characterizing the textbook as "an educational failure".

One of the currently–dominant areas of research in science education is the nature of science. As indicated earlier, the emphasis on the nature of science seeks to impart a more accurate picture of science as characterized by philosophers of science. Universally, research has shown that science education does a very poor job at conveying an accurate picture of the nature of science. What exists, in effect, is a major incompatibility between the nature of science and the nature of *school* science. And, the nature of school science can be identified with normal science education as defined above.

In Kuhn's 1963 characterization of normal science he observes that

> The single most striking feature of scientific education is that, to an extent quite unknown in other creative fields, it is conducted through *textbooks*, works written especially for students. Even books that compete for adoption in a single course *differ mainly in level and pedagogic detail, not in substance or conceptual structure.* (1963, pp. 350–351, italics in original)

Furthermore, Kuhn attributes this fact to an apparent tacit agreement among scientists as to what should be the elements of a pre–professional curriculum. Of course, this has led to the overcrowded curriculum syndrome in which the favourite topic of nearly everyone "has to be" included in the curriculum. However, the most important feature of textbooks, and the only part that many students pay attention to is the end of chapter problems. Kuhn claims that

> These books exhibit, from the very start, concrete problem–solutions that the profession has come to accept as paradigms, and they then ask the student either with a pencil and paper or in the laboratory, to solve for himself problems very closely modelled in method and substance upon which those through which the text has led him. (1963, p. 351)

The whole point of this method is to strip all "unnecessary" material and leave only the bare decontextualized scientific facts, theories, and laws along with the exemplar problems that demonstrate them.

The claim implicit in textbook–centred teaching that the "bare facts" and exemplars are adequate for obtaining an understanding of science seems to be based on a transmission model of teaching and learning. The transmission model treats information as a commodity that can be transmitted unchanged from the teacher to the mind of the student through the process of "telling".. This view goes back at least to John Locke in the seventeenth century. Locke, in his *Essay Concerning Human Understanding*, metaphorically speaks of the mind as a *tabula rasa*, a clean slate, which is "written" on by the sensory experience of listening to the teacher speak. Learning theory has departed radically from this traditional form during the last quarter of the twentieth century. In the vein of Locke's metaphor, today the mind of the learner is seen not as a clean slate, but rather a slate on which much is already "written", where the learner himself or herself "writes" new words and phrases in appropriate spots and rearranges phrases to make room for new ones.

The constructivist movement has produced the main opposition to this "traditional" view of learning. Von Glasersfeld, a major proponent of constructivism, states the essence of the constructivist philosophy when he writes: "Knowledge is the result of an individual subject's constructive activity, not a commodity that somehow resides outside the knower and can be conveyed or instilled by diligent perception or linguistic communication" (1990, p. 37). Learning is, then, a sense–making activity by the learner whereby she or he tries to accommodate new information to existing mental structures. New information is always connected to similar information where conceptual overlap or context is the dominant factor. By this path of reasoning one again arrives at the importance of context to the learning process, since information cannot exist in isolation in long–term memory and, even in the reasoning process, there are constant attempts to make connections among concepts.

The Practical Context

Of the five important contexts for teaching and learning science identified in the previous chapter, the first that will be considered is the practical context. The term "practical" is used here in the sense expressed by Derek Hodson (1993) who used it to refer to hands–on student laboratory work. Often, laboratory work is defined, after Hegerty–Hazel (1990), as "a form of practical work taking place in a purposely assigned environment where students engage in planned learning experiences … [and] interact with materials to observe and understand phenomena" (p. 4). What counts as practical work is relatively uncontroversial, but what the purposes of practical work should be is open to a number of differing opinions (Hodson, 1993; Lazarowitz & Tamir, 1994). Hodson (1993) categorizes the various objectives into five broad areas: to teach 1) laboratory skills and 2) scientific attitudes, 3) stimulate interest, and enhance learning of 4) the scientific content and 5) the nature of scientific methodology. Categorizing objectives in a general sense such as done by Hodson is one approach to understanding the purposes. In a considerably more explicit approach, Klassen (2000) compiled a list of the various purposes that have been espoused in universities for laboratory work in physics

I. Purposes not closely linked to course lectures

1. Instrumental and Measurement techniques
    a) Vernier and micrometer type measurements of length and angle
    b) Analog and digital meter operation and reading
    c) Oscilloscope measurements
    d) Circuit set–up from circuit diagram
    e) Operation of an instrument based on the users' manual
    f) The operation of various spectrometer type devices
    g) Photographic film techniques

2. Observational Skills
   a) Developing experience in various observational techniques
   b) Teaching students to interpret observations as relationships among variables
3. Record–keeping of Experimental Data
   a) Designing and constructing data tables ahead of time
   b) Keeping appropriately documented records of lab activities
4. Data Analysis Techniques
   a) Curve fitting techniques, especially the linear regression
   b) Familiarity with various computer resources like MathCad and Excel
5. Error Analysis
   a) Identifying sources of experimental uncertainty
   b) Standard Deviation
   c) Calculus propagation of errors
   d) Statistical error calculation, especially in slope and intercept
6. Drawing Conclusions From Data
   a) Any conclusions must be warranted on the basis of the error analysis

7. Ability to Write a Clear and Concise Laboratory Report
   a) In senior years, this would include the ability to write a formal report, including an abstract and introduction.
8. Ability to Present a Report Verbally
9. Experiment Design by the Student
   a) Ability to design experimental procedures to answer a question or support a thesis statement
   b) Ability to move beyond "cookbook" style labs to research–style investigations
   c) Ability of student to assume more responsibility
10. Development of Collaborative Learning Skills

II. Purposes Linked to Course Lectures

1. To help in the learning of underlying concepts
   a) Labs before lectures
      i. To uncover and correct aphysical student ideas
      ii. To introduce concepts before lecture to enhance the amount of learning that takes place in the lecture
      iii. To supplement the lectures in order for the student to develop physical intuition about concepts
      iv. To raise questions that will be further developed in class
   a) Lectures before Labs
      i. To support concepts developed previously in the lecture and provide an evidential basis for them

ii. To provide the student with experience in the physical world to supplement and complement the "world of ideas".

III. To Learn About the Nature of Science

Table 5: Purposes of University Physics Laboratories

(see Table 5). This list comprises most of the objectives that relate to laboratory work at any level throughout the university physics curriculum and includes the more traditional aspects. The traditional laboratory concentrates primarily on what Hodson (1993) categorizes as laboratory skills and secondarily on improved content knowledge. The objective of providing improved understanding of the nature of science methodology, in Hodson's terms, is a recent addition to objectives in the university laboratory. The development of scientific attitudes is a relatively minor aspect of the Klassen list—only group work, which may contribute to the ability to work cooperatively in teams, could be construed as a scientific attitude. However, there is nothing in the objectives that would prevent the development of scientific attitudes like objectivity and openness. One would suspect that, as in the case of nature of science, such objectives need to be taught explicitly in order to make a difference (see pp. 40–41). The more traditional student laboratory approaches have tended not to emphasize the psychological aspects of practical work, like motivation and interest. Contemporary developments in pedagogy have confirmed that the psychological or affective domain has a profound effect on learning. The affective context will be dealt with in a later section. As an aspect of practical work, then, the infusion of motivational elements seems to flow naturally from sound pedagogical and philosophical principles.

An alternative way to categorize practical work is by means of a methodological spectrum. For example, Stinner (1995) divides laboratory activities into three types: type I—instantiation types of experiments that operate in "cook–book" style; type II—research style experiments that attempt to answer questions not familiar to students in an open–ended approach; and type III—thought experiments that attempt to illuminate questions about theory by constructing hypothetical experiments or arguments that support or disprove various fundamental hypotheses about nature. In a somewhat similar fashion, Roth and Roychoudhury list four categories of laboratory activities on a scale of increasing "openness":

> 0 Problem area, methods of solution, and correct interpretation given or obvious. Includes observation and experience labs, or labs designed to teach new techniques.
> 1 Lab manual poses the problems; describes ways and means by which the student can discover relations he doesn't already know.
> 2 Problems are posed by the lab manual, but methods and answers are left open.
> 3 Problems, answers, and method are left open. The student is confronted with raw phenomena. (Roth & Roychoudhury, 1993, p. 129)

Approaches such as those by Roth and Roychoudhury or Stinner tend to be practical insofar that they concentrate on the degree of engagement of students in practical work. In their view, all student practical work lies on a spectrum whose one extreme is represented by instantiation or cookbook type experiments and the other extreme by student research work. Another way to characterize this spectrum is by the degree to which student practical work is like "real" science. Cookbook labs are not at all like scientists' science, whereas student research, if teacher–directed, can be very much like “real” science. This type of categorization scheme lends itself to the development of the large context, which, itself, is an open–ended or research–like approach.

The student, however, sees practical work from a completely different perspective than the teacher or researcher, in which the goals are primarily to follow sometimes meaningless instructions and to get the “right” answers (Hodson, 1993; Lunetta, 1998; Petrosino, 1998). The laboratory presents a daunting set of tasks for the student, the purposes for which are not at all clear in her or his mind. In the typical laboratory the student must a) understand the nature of the problem, b) understand the procedure, c) develop a theoretical perspective, d) read, comprehend, and follow directions, e) insure that they are getting along with their partner, f) operate the apparatus and collect data, and g) interpret results and write a report (Hodson, 1993). Hodson points out that the complexity of the task is frequently beyond the capabilities of the student, whereupon the student may resort to various coping mechanisms. According to Hodson, one way to deal with the complexity is for the teacher to simplify and isolate the tasks further (1993). Other researchers would disagree with Hodson’s (1993) solution (Blumenfeld, et al., 1991; Lunetta, 1998; Petrosino, 1998; Roth & Roychoudhury, 1993; Stinner, 1995) choosing instead to focus on producing a greater degree of contextualization of the labwork and on producing student motivation for and engagement with the task. Basing the design of practical work on lists of objectives tends to encourage breaking down the tasks into constituent components, thereby compounding the degree of isolation and decontextualization already present in much of science education.

Task Isolation Versus Contextualization

In the face of the challenge that reforming student practical work represents, it is a temptation to simplify the work and break it into components that represent the constituent objectives. The tendency towards task isolation can be seen as a holdover from behavioural psychology. However, developments in psychology and philosophy in the latter half of the twentieth century show task isolation to be an unjustified tactic, rooted in behaviourism.

Behaviourism, at least partly, grew out of an empiricist philosophy of science, which held that all knowledge originates in experience. The empiricist view has its origins in Aristotle's notion, as stated by medieval scholars, *nihil in intellectu quod non prius in sensu* – "There is nothing in the mind except what has passed through the senses." If one accepts Aristotle's dictum, then it follows that the mind merely consists of representations of sensory stimuli, which are the result of verbal teaching and reading. The implication of this early empiricist view is that knowledge can be transferred intact from teacher to student through the senses. John Locke was a major proponent of early empiricism. What the student learns, in the empiricist view, is an exact representation, or at least a subset, of what the teacher conveys, since no further processing is involved beyond the sensory transduction of information.

An implication of the empiricist–behaviourist view is that knowledge can be "atomized" or broken up into small, simple steps that are easy to teach and learn. The atomistic view of knowledge follows from the assumption that knowledge–based sensory stim-

stimuli are associated on a one–to–one basis with the cognitive representations of these knowledge items. The relationship of one mental knowledge–representation to another cannot be changed at the cognitive level in the behaviouristic view. The influential Harvard psychologist, B. F. Skinner, developed and popularized the atomistic view of knowledge and wrote: "The whole process of becoming competent in any field must be divided into a very large number of very small steps, and reinforcement must be contingent upon the accomplishment of each step" (Skinner, 1954, p. 94). The sequence of knowledge presentation becomes very important under the assumption that knowledge can be atomized and assimilated piecemeal. If knowledge is structured by the brain in the order that it is received (with no further internal re–processing), then relationships must be pre–formed in order for that knowledge to make sense. The sense–making, sequential, logical structure of knowledge must be pre–programmed into the process. Learning is thus viewed as a linear sequential process. Skinner details the formula for successful learning in the linear sequential view:

> If a learner attains the objectives subordinate to a higher objective, his probability of learning the latter has been shown to be very high; if he misses one or more of the subordinate objectives, his probability of learning the higher one drops to near zero. (1965, p. 30)

Finding out if the learner has missed learning objectives is the short–range objective of traditional science instruction and has resulted in the familiar teach–test–teach–test sequence.

As a result of the atomistic view of learning the component skills or knowledge items may be mastered independently and out of context as long as they are in the correct logical sequence. The contextualization of knowledge runs counter to the presuppositions of behaviourism since any contextual factors are either irrelevant to the items being taught or interfere with a narrow and clear presentation of the knowledge item. It should be no surprise, then, that the behaviouristic view of learning has been characterized as having two central assumptions—those of decomposability and decontextualization (Resnick & Resnick, 1992). The term "decontextualization" is a better one to use than, for example, "noncontextualization," since "decontextualization" implies the process of removal of knowledge items from the context in which they naturally exist.

Traditional instruction values simple factual recall through rote memorization. Simple facts that are memorized verbatim by the student may be regurgitated on a test and come back to the teacher unchanged. Strike and Posner reject rote learning, stating that

> the task of learning is primarily one of relating what one has encountered … to one's current ideas… . To learn an idea any other way is to acquire a piece of verbal behaviour which one emits to a stimulus, rather than to understand an idea which one can employ in an intellectually productive way. (1985, p. 212)

Strike and Posner's criticism of traditional teaching and learning is typical of the view that has brought about dissatisfaction with traditional instruction, which, for the most part, relies on simple factual recall. The factors that led to these criticisms and to the abandonment of some of the traditional presuppositions and methods grew out of a psychological and philosophical paradigm shift around the 1970's. The shift generally moved from the empiricist–behaviourist dominated paradigm to one based on cognitive psychology, constructivism, and the philosophical positions of philosophers of science, such as Thomas Kuhn.

The Demise of Behaviourism

The course of the psychological and educational paradigm was greatly affected in 1959 by the unlikely field of linguistics and the involvement of the influential linguist, philosopher, and activist Noam Chomsky (Corsini, 1994; Houts & Haddock, 1992). Although linguistics is not directly related to science education, Chomsky's involvement was a major initial factor in producing the paradigm shift that included science education. Chomsky published a review of B. F. Skinner's book *Verbal Behaviour*, in 1959. In his book, Skinner had attempted to show that behaviouristic stimulus, response, and reinforcement mechanisms govern language development. Chomsky argued that Skinner's model was unable to account for the complexities of language development. Moreover, Chomsky maintained, to say that each language element is a response to a stimulus is a scientifically meaningless claim since a stimulus can always be posited to explain any response (Chomsky, 1959). It was easy to see, in Chomsky's account, that if a process of hearing and repetition were to be the exclusive mechanism in language learning, it would take a person an incredibly long time to hear and repeat enough variations of grammar and syntax in order to learn a language—much longer than is the case. Chomsky's paper marked the beginning of the demise of behaviourism and the rise of cognitive psychology. Much later, Chomsky's critique was challenged (Houts & Haddock, 1992), but by then it was too late to change a historically established fact. It was not long before the views of cognitive psychologists, among them Piaget, and philosophers of science, among them Thomas Kuhn, began to gain prominence. Behaviourism gradually diminished as a viable theory. It is generally accepted that behaviourism has been displaced as a viable theory (Black, 1993; Shepard, 1991; Willson, 1991), but some versions are still active (Houts & Haddock, 1992).

A New Approach to Student Practical Work

Granted that the atomization of knowledge and tasks is a discredited approach to teaching, the goal of achieving a higher degree of contextualization is an important aspect of reform in student practical work (Gil–Pérez, 1996; Petrosino, 1998; Roth & Roychoudhury, 1993; Stinner, 1995). Similarly, the consideration of student motivation should also play a much greater role in the design of practical work (Blumenfeld, et al., 1991; Gil–Pérez, 1996; Lunetta, 1998; Petrosino, 1998). Roth and Roychoudhury (1993) identify a key reason that contextualization is linked with motivation when they observe that "the effects of motivation and context on student learning … appear to interact with the authenticity of situations and experience" (p. 147). The authenticity of student work is increased by its degree of open–endedness, as was illustrated earlier in Roth and Roychoudhury's classification scheme for practical work. Blumenfeld, et al., (1991) shed further light on authenticity by pointing out that practical work needs to be driven by motivating questions, problems or issues. In this way, students are aware, from the start, of the purpose of the work and thereby are rescued from the dilemma of being confused about the purposes for practical work in the first place (Hodson, 1993; Lunetta, 1998; Petrosino, 1998). The driving situation for practical work is not only the "motivation" for the student activities that follow, but also provides motivation, in the affective sense, for the students. For these reasons, motivating questions or themes are central to the design of practical tasks.

Another important aspect to developing an overall philosophy, approach, or theoretical structure behind practical work is the driving metaphor for student learning in the laboratory situation. As was described earlier, a recurring metaphor in science education is that of student as early scientist. Much has been written to support the contention that there are similarities (or differences) in the thinking of students and early scientists (see Chapter 2). Recently, the "theory theory" movement (Brewer & Samarapungavan, 1991; Gopnik & Meltzoff, 1997; Schwitzgebel, 1999) contends that, essentially, the differences in theorizing between scientists and students are only differences of degree, not differences of kind. Gil–Pérez and Carrascosa–Alis (1994) rescue the metaphor from serious challenges by proposing a similarity between students engaged in authentic practical work and novice researchers. Indeed, if this metaphor is applied at the university level it stops being a metaphor, becoming, instead, a plausible model of the role of the student. A plausible or realistic model in any theory presents an interesting situation. Models in theories have the role of representing problematic phenomena in terms of better–understood schemata. When the model becomes realistic it assumes, or nearly assumes, identity with the situation it is supposed to represent. According to philosopher Rom Harrè (1961), a model becomes realistic when its parent theory achieves a high degree of maturity, acceptance, and confirmation. In our case, since we are in the process of constructing a theoretical framework, Harrè's commentary can be noted as an encouraging perspective.

The model of student as novice researcher helps to clarify the ambiguity in the purposes for student practical work. In the large context, under the guidance of the instructor, students generate their own questions and problems to investigate, and they design their own procedures. In this respect, the process is more like that of scientific research, where a research team functions under the leadership of a research director (the teacher). This type of classroom activity is characterized by Ebenezer and Fraser (2001) as "common knowledge construction" (p. 513) and they maintain that

> … to arrive at common knowledge, … we must think of the science classroom as a forum for scientific discourse. To characterize such a classroom, the teacher should entertain qualitatively different conceptions from students; assess students' conceptions; … help students collect evidence to support knowledge claims; allow students to generate, formulate, and evaluate their arguments and other students' arguments; and help students make decisions among competing knowledge claims so they may come to an agreed upon "outcome space." (p. 513)

The objective is to transform the classroom into "a forum for scientific discourse" so that students can function as novice researchers.

Ultimately, the practical context is meant to replace traditional "labs" in the "normal science" curriculum. Students who are potential scientists benefit from practising as novice scientists, since they are only one step removed from being apprentices. Even students who have no intention of becoming scientists benefit from participating in an authentic activity that includes creativity and some intellectual challenge beyond guessing what the lab manual wants.

The Theoretical Context

As in scientific research, in the large context there is an opportunity for both the experimental approach and theoretical model for a problem to be worked out. There is good reason for the practical and conceptual aspects of science education to operate side by side. The reasons go back to the insight that observations in science tend to be theory–laden.

According to cognitive psychology, understanding is a mental process of perceiving and knowing. Sensory stimuli, such as sight, assume a secondary role. N. R. Hanson succinctly expressed the subordinate nature of sensation to thought when he wrote,

> People, not their eyes, see. Cameras and eye–balls, are blind. Attempts to locate within the organs of sight (or within the neurological reticulum behind the eyes) some nameable called 'seeing' may be dismissed. That Kepler and Tycho do, or do not, see the same thing cannot be supported by reference to the physical states of their retinas, optical nerves or visual cortices: there is more to seeing than meets the eyeball. (1958, pp. 6–7)

What Kepler and Tycho Brahe understood about the heavens was not dependent primarily on the observations that they used in their work, which were the same, but on their understandings about those observations. That Kepler and Brahe, using the same data, came to different theories suggests that the process of understanding takes place beyond sensory perception. Cognitive psychology turned the attention of learning theory decisively to the active cognitive processes of the individual, and early proponents of this view, for example, Hanson, saw evidence for active cognitive processes in the history of science.

Other early views of cognitive processes, like that of Chomsky about inherent learning abilities, implied that science understanding, like language understanding, stemmed from a complex cognitive structure. Piaget was sympathetic to Chomsky's thesis about language learning and pointed out (1968) that his work, like Chomsky's, rejected the empiricist–behaviourstic view. Piaget reflected that "I find myself opposed to the view of knowledge as a copy, a passive copy, of reality" (1968, par. 24). The empiricists considered logic as a linguistic convention whereas Chomsky saw language as based on innate reason (Piaget, 1968). Cognitive structures, such as language learning ability, were seen by Chomsky as innate to the learner. This early static view of cognitive abilities is similar to the notion of innate abilities such as "scientific ability".

Piaget's view of science learning, however, emerged as a much more dynamic entity. The alternative view of Piaget, which did much to promote the cognitive–psychological and constructivist paradigms and the emerging philosophy of science is articulated by Piaget in the following excerpt:

> The current state of knowledge is a moment in history, changing just as rapidly as the state of knowledge in the past has ever changed and, in many instances, more rapidly. Scientific thought, then, is not momentary, it is not a static instance; it is a process. More specifically, it is a process of continual construction and reorganisation. This is true in almost every branch of scientific investigation. (1968, par. 3)

Piaget and other members of the new cognitive, constructivist, and philosophical paradigms saw a similarity between historical knowledge developments and knowledge structures of the mind as no accident (Duschl, Hamilton, & Grandy, 1990; Piaget, 1968). The historical development of scientific knowledge was postulated to hold valuable information as to how knowledge developed in the individual. In this sense, the historical recapitulation thesis is not unreasonable, seeing that both the science student and the scientist use dynamic cognitive processes to assimilate information about the world (see Chapter 2). Although the scientist is a highly exceptional and gifted individual, she or he employs cognitive processes similar to everyone else, according to cognitive psychology.

The views of learning of Piaget had a major influence on Thomas Kuhn. Kuhn states: "Part of what I know about how to ask questions of dead scientists has been learned by examining Piaget's interrogations of living children" (Kuhn, 1977, p. 21). One of Kuhn's major contributions was to challenge the separation of philosophy and psychology (Giere, 1992). Two notions on which philosophy of science and cognitive psychology came to agree were in the notions of theory–ladenness and the importance of context. The philosophy of science, especially in Kuhn's formulation, saw all experimental observation as being theory–laden. According to Kuhn's thesis, the paradigm determines how a community of scientists will see the world, what questions they will find interesting, and what kinds of solutions to problems are possible. The understandings of a paradigm dictate the interpretation given to observations and even what kinds of observations can be made (Kuhn, 1996). Hanson stated as early as 1958 that "a theory is not pieced together from observed phenomena; it is rather what makes it possible to observe phenomena as being of a certain sort, and as related to other phenomena" (p. 90). More recently, the philosopher of science Paul Churchland writes that theory–ladenness is natural to all cognitive activity (1992).

A moderate interpretation of theory–ladenness is that all observation must take place from a particular conceptual perspective in order for meaningful interpretation to take place. In this form theory–ladenness is a fairly unproblematic assumption and has important consequences for student work. One would expect that in order for students to develop an understanding of science the theoretical aspects could not be divorced from the practical aspects. In line with this insight, Derek Hodson maintains that "students can only develop their procedural knowledge and process skills within particular theoretical contexts" (1993, p. 111). Gil–Pérez (1996) further proposes as a fundamental assumption in science education that learning scientific knowledge, learning about the nature of science, and doing science are inseparable. One might say that in order for significant learning to take place students must engage in practical work together with the manipulation of ideas (Lunetta, 1998).

The "manipulation of ideas" of the theoretical context is meant to replace paradigm exemplars of the type that students learn in normal science education (see page 76). As was discussed earlier, normal science education relies heavily on end of chapter questions to provide student learning experiences. These problems are usually contrived and remote from students' life experiences. In contrast, problems in the theoretical context emerge as a natural necessity in the course of investigations. Ideas or concepts take on meaning as they are naturally generated by the context. The theoretical context, however, is dependant on the practical context to provide a well–rounded learning opportunity. As in the practical context, students are cast into the role of being novice researchers.

The Social Context

One of the contexts of learning as outlined in the previous chapter is the social context. Again, the analogy of student as novice researcher requires that the school experience should contain real–life elements implying that learning together with others should be a major element in classroom activity. The term “cooperative learning” is generally applied to groups of students from the same class working together (Herreid, 1998; Johnson & Johnson, 1989). Cooperative learning, as a movement, began with the American desegregation process in junior high schools (Slavin, 1980). One of the major goals then was the facilitation of positive ethnic relations. Since then, other potential benefits of cooperative learning have come to light and dominate the reasons for employing the technique. Cooperative learning has grown to be a major educational movement in its own right and may be one of the most investigated classroom methods in educational research (Herreid, 1998). David and Roger Johnson of the University of Minnesota are probably the most cited in the field of cooperative learning and their five elements of cooperative learning are universally quoted when introducing the topic. The five essential elements of successful cooperative learning as formulated by Johnson and Johnson (1989) are 1) positive interdependence 2) individual accountability 3) face–to–face promotive interaction, 4) use of teamwork skills, and 5) group processing.

In a cooperative learning group, each member must believe that she or he cannot succeed without the other members and that others cannot succeed without her or him, yet any group member cannot ride on the coattails of another, and each one must make a genuine contribution. Face–to–face interaction makes possible oral explanations of how to solve problems and generally fosters a supportive atmosphere. As the group members learn to work together, they will develop skills in leadership, organization, communication, and conflict management. As the work progresses, it is essential that the group assesses how well they are doing and whether they are likely to meet their goals.

Although cooperative learning is a very active field with numerous published strategies on its implementation, incorporating it would benefit from knowledge about its theoretical foundations. A theoretical basis for cooperative learning is found in the work of the Russian psychologist Lev Vygotksy (Doolittle, 1997), whose major works were not published until after his death in 1934. Vygotsky was the primary originator of social constructivism, a theory of learning that assumes the importance of social factors in knowledge acquisition (Matthews, 1994).

A Theoretical Basis for Cooperative Learning

The most well–known component of Vygotsky's theory of learning is his zone of proximal development. Vygotsky, like other cognitive psychologists and constructivists, believed that "concepts are not ready made" (Vygotsky, 1986/1934, p. 161). In their view, the learner actively constructs concepts as the result of social interaction. The student's potential for cognitive growth is limited, on the one hand, by what the student is able to accomplish on her or his own and, on the other hand, by what the student is able to accomplish with the help of a more knowledgeable individual. This range of learning ability is known as the zone of proximal development. Vygotsky illustrated his zone of proximal development by administering tests to children either without any intervention or with some hints or clues. He describes what happened:

> Having found that the mental age of two children was, let us say, eight, we gave each of them harder problems than he could manage on his own and provided some slight assistance; the first step in a solution, a leading question, or some other form of help. We discovered that one child could, in cooperation, solve problems designed for twelve–year–olds, while the other could not go beyond problems intended for nine–year–olds. The discrepancy between a child's actual mental age and the level he reaches in solving problems with assistance indicates the zone of his proximal development. ... Can we really say that their mental development is the same? Experience has shown that the child with the larger zone of proximal development will do much better in school. This measure gives a more helpful clue than mental age does to the dynamics of intellectual progress. (1986/1934, p. 187)

The gap in difficulty between what the student could do on his own to what "he" could do with assistance corresponds to the zone of proximal development. The normal process of learning in Vygotsky's view is a development from performing difficult tasks with assistance to performing the same level of task independently. When the student moves from the assisted end of the zone of proximal development to the independent end, development is greater than if the student were to attempt learning activities entirely on his or her own. Vygotsky's theory tells us that the primary benefit of cooperative learning will be to enable students to master performing difficult tasks or understanding concepts. Any implementation strategy must therefore seek to structure tasks so that there is adequate opportunity for students to work with others during the learning process.

The benefit of cooperation in assisting learning is a relatively uncontroversial fact. The benefits are likely to accrue not only in the form of improved learning of academic content, but in the learning of scientific and life skills related to social organization and leadership. In our context, making use of the assistance to the learning process naturally provided by cooperative learning requires careful attention to the structuring, organizing, and evaluating of group activities that are a part of the large context.

The Historical Context

Arguments establishing the value of the historical context to teaching were first presented in Chapter 2. The historical approach was seen to have been justified on scientific, pedagogical, philosophical, and cultural grounds. Pedagogical considerations necessitated adopting the contextual view of knowledge acquisition and provided not only a firmer basis for *justifying* the inclusion of history of science, but also a basis for *developing* an approach for using that history in teaching. On that basis, the proposal that the teaching of science would derive much benefit from the historical context was elevated to the status of a *presupposition*. However, the development of any pedagogical approach that is meant to utilize history of science cannot proceed without considering what interpretation of history is to guide the selection and adaptation of historical materials.

History of science is subject to a broad spectrum of possible interpretations. On the one end of the spectrum is what Herbert Butterfield (1959/1931) called the whig approach to history in which history of science is viewed in light of current knowledge. Implicit in this approach is the assumption that current knowledge is superior to the knowledge of past scientists. Various terms have been applied to the "whig" approach, including vertical history (Mayr, 1990), and anachronical history (Kragh, 1987). The whig approach to interpreting history has been much criticized as an illegitimate view of the history of science (Butterfield, 1959/1931; Mayr, 1990). Critics of the whig approach object to applying current days' standards to history because historical figures operated in a different environment with different assumptions and standards than they do today. On the other end of the spectrum of approaches is the localized view in which history is interpreted only in light of the knowledge and context of the time and place in question. This approach, referred to as horizontal history by Mayr and diachronical history by Kragh, has been criticized on the grounds that history cannot be interpreted when comparisons to the larger context cannot be made (Mayr, 1990; Kragh, 1987). Furthermore, it has been claimed that purely diachronical history is uninteresting to the non–specialist in that it is a chronology of events restricted to the local context (Mayr, 1990; Kragh, 1987).

Beyond the spectrum of historiography for historians of science, which runs from the whig to the localized extremes, there are also internal histories of science written primarily by scientists, some of who participated in the events about which they wrote many years later. Such histories of science—written by scientists for scientists and science students—serve a different purpose from specialist histories written by historians for historians or students of history. Since the development of internal history is not subject to the same criticism as it would be within the disciplinary environment of history and since it serves different purposes, it quickly takes on a static nature. The purposes of such histories are to provide legitimization for the science, to aid in the socialization of novices, and to pass on exemplars that will be used as models for problem–solving (Kragh, 1987). Internal history provides an official version of the roots of the discipline that tends to romanticize the events and portray science as an inevitable consequence of the force of progress. Each event is portrayed as if it were a certain outcome of the carefully–chosen preceding events. What the reader of such history likely does not know is that many historical details, some of them arguably relevant, have been omitted. Internal history of science has been called ideological, official, or mythical history (Kragh, 1987). Exposing students only to this version of history encourages a distorted view of the nature of science and may have unintended consequences. Recently, Pedro Goldman, chair of the Division of Physics Education of the Canadian Association of Physicists, shared with me his observation that many younger students will not consider pursuing studies in physics because they believe that all the discoveries in physics have already been made and that physics is boring because there is nothing new. Such a view is likely the outcome of the portrayal of physics, through its mythical history, as the inevitable outcome of the force of progress. Ideological histories often will not include alternative explanations of phenomena, alternative theories, failed experiments, the inevitable sense of uncertainty, and episodes of debate and controversy. Internal histories, because they tend to be, in a way, personal, do not portray history of science in the manner advocated by Ian Winchester—"warts and all" (1989).

As an example of the pervasiveness of pseudo or mythical histories of science I refer to the popular and widely–used video series, *The Mechanical Universe and Beyond.*

In episode 24 the topic "Particles and Waves" is introduced. In interpreting Robert Millikan's experiments performed up to 1916 to measure the photoelectric effect the narrator of the video states:

> When he measured the energies of electrons ejected from various metals by different frequencies of light, Millikan verified that while each metal has a different work function, Planck's constant has the same universal value for all of them. But this explanation of the photoelectric effect not only confirmed Planck's theory, it showed directly that bundles of energy already exist in the electromagnetic field. (California Institute of Technology, 1987)

However, this popular presentation of historical events is factually incorrect. Millikan did not set out to verify, even indirectly, Planck's radiation formula or Einstein's photon concept, which he did not accept. He simply sought to establish the mathematical form of the relationship between ejected electron maximum energy and incident light frequency, not any particular theory behind the relationship (Kragh, 1992). Helge Kragh agrees with Thomas Kuhn that such quasi–histories of science are intended to "make students believe that they are participants in a grand historical tradition which has progressed cumulatively and according to definite methodological norms" (Kragh, 1992, p. 359). As I postulated earlier, such distorted views of the history of science may serve to produce negative attitudes towards science in young science students.

Although there is the potential for producing ideological and mythical histories of science that encourage misconceptions about science and history, there is also the possibility of harnessing history for the sake of conceptual clarification. On the one hand, school science has produced what might be called *conceptual distillation*, largely a distillation of history of science, which, like mythical history, fosters a distorted view of science. On the other hand, a balanced view of the origins of concepts can be utilized for *conceptual clarification* in the way that the physicist Maxwell explained long ago: "science is always most completely assimilated when it is in the nascent state" (1873/1904, p. xi). One way that history of science can illuminate currently–accepted concepts in science is to attempt to reconstruct the development of these concepts. In order to be truly useful, such a history must include the struggle to explain newly discovered phenomena by means of competing theories. Seeing how scientists put forth alternative explanations and finally settled on one explanation and how that explanation had to be modified as time went on will be useful in helping students come to a deeper understanding of current theory (see Chapter 2).

In view of the preceding discussion, history of science that is to be used for pedagogical purposes must tread a fine line through the pitfalls of extremes that could conceivably arise in interpreting history. Obviously, the origins of ideas must relate to the current understanding, which is the point from which history must, of necessity, be approached in education. However, a merely logical reconstruction of past events that produces pseudo–history, as in the example above, must be avoided. History must be placed in its original context, while relating it to our current views, in a manner that respects the originators and portrays them in a fair and balanced way. The objective of accuracy or faithfulness to the historical record must, in turn, be balanced against the demands of a curriculum that limit the depth to which the history can be probed. Lastly, it should be realized that the place of history is not only to make a conceptual point but also to introduce the humanistic element into the process of learning science. Portraying scientists as human beings and giving students the opportunity to become affectively involved in the *story* of science are worthy goals in themselves.

Content Analysis of Original Sources

The preferred approach to history of science in the educational setting could be described as an authentic approach. An obvious way to provide authentic history is to incorporate the original writing of historical figures. However, original writings may not always be suitable for student use. The analysis of original texts for their suitability could be regarded as a form of content analysis. That original writings need to be incorporated sensitively, if used at all, is manifestly demonstrated by Fritz Kubli (1999) in a study in which high school students were asked to rate various approaches to science teaching, including original texts, narratives, and historical experiments. Original texts met with general disapproval from the students. However, others (Fowler, 2001; Holbrow, et. al., 1995) have used original texts with considerable success. In my own experience, the acceptance of original texts by students depends, first of all, on the level of mathematical difficulty and the degree of student familiarity with the mathematical notation. Michael Fowler of the University of Virginia makes the same observation (2001). The teacher must be aware of the mathematical preparedness of students and make sure that original papers do not contain mathematics that is too advanced for students. Content analysis consists of a critical reading of the historical material to check for the level of difficulty of the mathematics. The level must match the mathematical preparedness of the students, something about which every good physics teacher is knowledgeable.

There are several other barriers to incorporating original sources. A second obstacle to the effective use of original sources is possible miscommunication due to discrepancies between the original and the contemporary meanings of technical and scientific terms, for example, the evolving meaning of "force" (Stinner, 1994). In this case, the evolution of the meaning of any such term used in original texts should be explicitly discussed with students before they read them. A third obstacle may be unfamiliarity with an older form of the language being employed in original texts, but that has not dissuaded other disciplines from incorporating such texts as, for instance, the inclusion of Shakespeare's works in English Language Arts curricula. The length of original texts can become another obstacle, due to constraints of time in teaching, and often original texts must be excerpted. Obscure mathematical symbolism may pose another difficulty and result in the necessity to translate it into a more familiar format for students, one that allows the mathematical techniques to remain essentially the same as the original (Kragh, 1987). Content analysis will consist of a critical reading of the historical material to check for the degree of obscurity of mathematical notation. Another possible weakness in content is that original historical material often appears as a chronology. Students will, however, respond more positively to materials presented in a narrative form (Kubli, 1999). Ideally, history must be recast into story form, using details that are historically accurate. The story is differentiated from a chronology in that it contains an intentional element (Egan, 1978; Martin, 1986; Prince, 1973; Reid, 1977). The addition of an intentional element to historical narrative requires historical interpretation because the historical facts often do not provide motivations and reasons for occurrences. It may be necessary to add plausible details that do not contradict known historical facts. Further consideration of the nature of stories is a study in its own right and is the subject of the next chapter.

The Affective Context

The important role played by the emotions in learning has been recognized only recently. Relevant, in this regard, is the research on emotion and rationality by neurobiologist Antonio Damasio. Damasio has studied human subjects who have lost the ability to communicate information about emotions from one part of the brain to the other. As a result, he has been able to support his hypothesis relating emotion and reason, which states that the emotions act as an arbitrator in rational decision–making and that without access to one's emotions, it is impossible to plan and make rational decisions (Damasio, 1994). Educator Douglas Barnes demonstrates, in a research study of student group learning, that "unless pupils are willing to take the risk of some emotional commitment they are unlikely to learn" (1992, p. 87). Cognitive psychologist Pierce Howard, in a popular review of current neurobiological research, further explains the role of emotions in learning this way: "Experience arouses emotion, which fixes attention and leads to understanding and insight, which results in memory" (Howard, 2000, p. 549). At issue is the means by which emotion could be aroused in an appropriate manner in the teaching and learning situation. Educator Kieren Egan (1989a) has long advocated the story form as a method of engaging students' emotions. Aside from Egan's work, and the more recent work of Kubli (2000) not much has been written on how student emotions may be constructively tapped through the telling (or reading) of stories and how stories in science may be constructed. Due to its complexity and relatively unexplored nature, this topic is set aside as the subject of the entire next chapter.

A Schema for the Story–Driven Contextual Approach

To differentiate the contextual model under development here from Stinner's LCPA, new terminology will be introduced at this point. To emphasize the important role of narrative to incorporate both history of science and the affective element through various levels of story and the central place of context, the theoretical framework will be called the *Story–Driven Contextual Approach* (SDCA). The approach, as it was conceptualized in this chapter, can be summarized in a diagrammatic fashion (see Figure 4). Such a diagram, while it could arguably be called a "representation of the problematic in terms of the familiar", as a model was defined, would best be called a conceptual scheme as described in Chapter 3, or, in short, a schema. At the heart of the schema is the definition of context given in Chapter 3: "the entities that connect to or surround a focal entity and contribute to the meaningfulness of the whole." At the heart of the contexts is the concept or ability (or concepts or abilities) that students are to learn. The learning process takes place amid the relevant contexts. Students will bring their ideas, attitudes, prior knowledge, and experiences to the whole learning process and, if the experience is to be considered a success, they will leave with somewhat changed (new) ideas, attitudes, knowledge, and skills. We would like the attitude with which students approach the

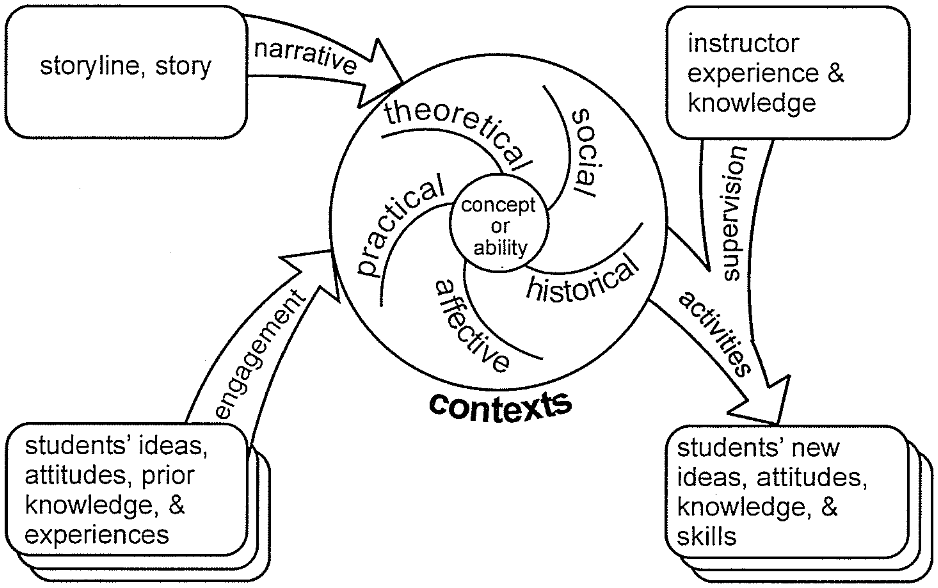


Figure 4: A Schema for the Story–Driven Contextual Approach

Story–Driven Contextual Approach to be one of involvement and commitment to the tasks. The word "engagement" carries that meaning, as opposed to, say, "predilection", which implies a preferential reaction to the instructional approach, which is more passive than emotional involvement. The schema is consistent with what is currently believed about the learning process. It has also become apparent that a science storyline or narrative approach must be a part of the process. This is visualized as another component entering the learning process. Two ways in which this might be done is by means of readings and by means of a story told by the teacher. Furthermore, in the model of student as novice researcher, the teacher plays the role of research leader and provides expert advice and supervision as the students begin to formulate ideas and perform activities that will ultimately culminate in some form of report, perhaps verbal. Consistent with the constructivist model of learning, the teacher is not seen as directly affecting the minds of the students by way of an input, but as a director of activities, affecting the output of the process. Placing the role of the teacher one step removed from the centre is, perhaps, novel—it certainly communicates the perspective that students are to be given a high degree of responsibility for their own learning. This schema is now to serve as a representation of the Story–Driven Contextual Approach in future discussion and development.

Chapter 5

A THEORETICAL FRAMEWORK FOR STORY AND ITS IMPLICATIONS FOR LEARNING

It has always been apparent to good teachers that stories make learning experiences memorable. When I asked my university students if they recalled stories their teachers had told them in high school, one student shared with me that the only thing he could recall explicitly from his high school classes was a story his mathematics teacher had told in class. That student's response is typical of many I have heard. One of the main reasons that stories make learning experiences memorable is their ability to stimulate an emotional response in students (Egan, 1986, 1989a,b; Miall & Kuiken, 1994). Others have argued that the story is a device that imposes coherence on a set of events (Kenealy, 1989) and thereby is a suitable vehicle for the integration of history of science in science instruction. The inclusion of story in the presentation of history in science teaching has been advocated and attempted by a growing number of science educators (Kenealy, 1989; Kubli, 1999; Martin & Brouwer, 1991; Stinner, 1992; Wandersee, 1990); however, a theory for doing so has not been developed to any significant extent. In order for stories to become truly useful in producing better learning of content knowledge, their relationship to the learning process itself must be explored. Should the story be considered a major component of science instruction? Levi–Strauss (1966) and Bruner (1996) have postulated that the story form corresponds to an underlying cognitive structure that may have a genetic basis, and if they are right, the story must indeed be viewed as essential.

The Characteristics of a Story

There are almost as many perspectives on the story form as there are narrative theorists. Nevertheless, a definition of "story" is valuable in differentiating the story form of discourse from other forms, say, those used in science textbooks. The most evident feature of stories is that they are an account of a temporal sequence of events that possess a causative or intentional element (Egan, 1978; Martin, 1986; Prince, 1973; Reid, 1977). Stories usually involve the actions of humans or human–like agents (Bruner, 1996), unlike science writing that strives to eliminate the subjective or human element (Locke, 1992). Various theorists single out different characteristics of the story form as being of primary importance. Egan (1989a) singles out the affective element of a story as the most important feature. For Kenealy (1989) the element of coherence is primary in the construction of a story. Another important characteristic of the story may be the stimulation of the imagination in the reader or hearer, an important feature in the development of scientific concepts (Egan, 1989b; Stinner, 1990). Bruner (1996) claims that "stories are judged on the basis of their verisimilitude or 'lifelikeness' " (p. 122). Both Bruner and Karl Popper use the term "verisimilitude", but their meanings are different. Bruner uses the term "verisimilitude" to describe the natural form of expression in the humanities and Popper to describe the natural form of expression in the sciences. The sciences, Bruner maintains, are concerned with well–formed, logical arguments. Popper (1979) would say that the sciences aspire to true theories. The degree of closeness to truth Popper defines as verisimilitude. Popper's verisimilitude could be expressed as "truthlikeness". On the other hand, the humanities, Bruner maintains, aspire to "understand the world as it reflects the requirements of living" (Bruner, 1986, p. 50). Bruner's verisimilitude could be expressed as "lifelikeness". Although a well–formed story is lifelike, it may also aspire to truth, but in a different sense than that described by Popper. One might say that scientific theories must be "true of life" since they aspire to be accurate descriptions of the world, but that they must *not* be "true to life" as is the case of stories that seek to express the subjective character of personal experiences. Bruner maintains that stories are basically different from scientific arguments in that the scientific argument appeals to logic whereas the story appeals to our sense of human identity. However, if stories are interwoven with accurate historical and scientific details, then they may be both truthlike and lifelike at the same time.

Likely, the most important characteristics of the story relate to the story's extraordinary ability to evoke affective engagement and memorability. The issue is how various features of the story might be crafted into a theoretical framework that benefits learning. Egan suggests that one "extract from the basic story form a framework" (1989b, p. 458) that may be used to guide the planning of instruction. In a similar vein, Bruner recommends that we "convert our efforts at scientific understanding into the form of narratives" (1996, p. 125). In order to understand the story *form* and attempt to relate it to a type of learning *process*, it is likely that a structuralist approach (an analysis of the story's form) would be a productive path to follow. Structuralism is a school of literary criticism that derives its principles from scientific linguistics. It attempts to analyse literature in terms of the relationships among its constitutive linguistic elements. Since the most obvious feature of the story is its structure—beginning, middle, and ending—my search for a theory of story began with structuralism. My first step was to gain a structural understanding of the story form.

The Structure of a Story

Almost universally, story theorists have pointed out that a story must have a beginning, middle, and ending. This insight originates with Aristotle's *Poetics*. Structuralists, such as Prince (1973) and Bremond (1980), have elaborated on this three–stage structure of the story. Narratologist Gerald Prince of the University of Pennsylvania (1973) constructs his theory of the "minimal story" by posing, evaluating, and analyzing a large number of story–like sentences. He distinguishes those sentences that qualify as a story from those that do not. In Prince's theory, the minimal story consists of three narrative units where the second and third follow the first sequentially in time. In Prince's words,

> [a] minimal story consists of three conjoined events. The first and third events are stative, the second active. Furthermore, the third event is the inverse of the first. Finally, the three events are conjoined … in such a way that (a) the first event precedes the second in time and the second precedes the third, and (b) the second event causes the third. (Prince, 1973, p. 31)

Prince uses the word "event" for each structural unit, but I have adapted his terminology and use the word "state" for the first and third "events" and "action" to designate the second "event" (see Figure 5). In this rendering of Prince's model, there are two states with

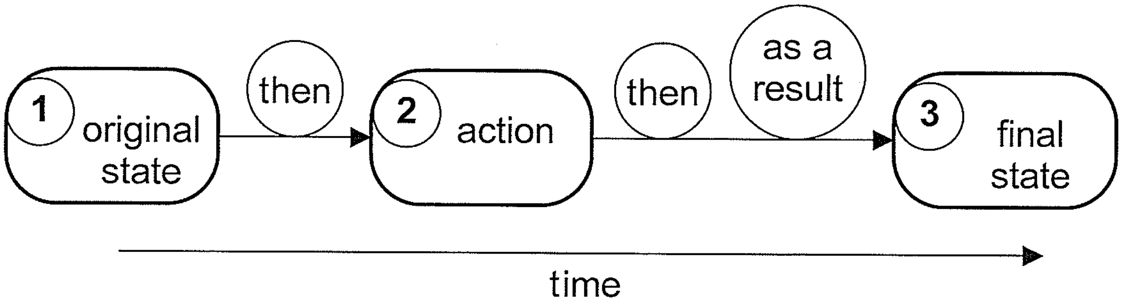


Figure 5: The Minimal Story Sequence

an intervening action. The requirement that the original state and final state are the inverse of each other is consistent with the story model of Egan (1986), who requires stories to tell about binary opposites. Pairs like unhappy–happy, poor–rich, and unsuccessful–successful traditionally comprise the state–inverse state pair. Egan adds pairs like hot–cold and heavy–light for using in his story form adapted for teaching science to children. If historical episodes in science are analysed as story–sequences, they may yield binary sets of states that may not always be described as opposites, as we will see below. Hence, I employ the term "state pair" rather than Egan's term "binary opposites". The term *state pair* allows the possibility that events may be related in a way that cannot be described as opposites. In historical science stories there may be state pairs like curious–informed, not knowing–knowing, frustrated–successful, and dissatisfied–satisfied. Many of these pairs, like, for instance, not knowing–knowing, are idealized forms—they are extremes on a continuum that holds real–life situations.

How would the minimal story sequence be applied to history of science? As an example, we might consider the story of the development of Ohm's law. Some simple story–like sentences will be posed by way of illustration. A simple story sequence describing Ohm's career would be

> *Ohm was unsuccessful,*
> *then he published his experimental results,*
> *and, then, as a result, he became successful.*

Other historical sequences would, however, not have a story–like quality. For example, the three–event sequence

> *Ohm took up a teaching position in Cologne,*
> *then he performed an experiment to determine resistance,*
> *and, then, he published his experiment*

is not a story–sequence. While there is an implied causative link between the original and final state, the final state bears no inverse relationship to the original state. Furthermore, the original and final states are better described as actions, rather than states. Other story sequences are closer to Prince's scheme:

> *Ohm understood the mathematical theory of heat,*
> *then he applied the theory to electricity,*
> *and then, as a result, Ohm understood the mathematical theory of electrical resistance.*

The element lacking here is an inverse relationship between the initial and final state. However, the two are clearly related, namely, "Ohm understood A" can be transformed into "Ohm understood B" by replacing A with B. Prince points out that the requirement of inversely related states is the primary difference between story and history. It would be difficult to construct many true story sequences that are also true to history, unless this condition were relaxed. The events of history are real, not created as in a fictional story, and succeeding real events are rarely the inverse of each other. In the spirit of the previous example, I propose that, instead of requiring an inverse relationship between the original and final states, simple transformational relationships, like the example above, be accepted. That is to say, the initial and final states may be related by a simple transformation. Hence, the following sequence would also qualify as a story sequence:

> *Ohm was convinced that his mathematical expression for resistance was correct,*
> *then he received the British Copley medal,*
> *and then, as a result, many German scientists were also convinced that his mathematical expression for resistance was correct.*

Here, the original state is transformed from the form "A was/were convinced that his mathematical model of resistance was correct" to the final state, which is another statement of the same form in which B is substituted for A.

If real stories were constrained to fit this model exactly, then they would be awkward and stilted, at best and inaccurate and untrue, at worst. However, the framework of a story need only contain the minimal story sequence features implicitly. Furthermore, stories are complex devices that contain many minimal story sequences that are related in complex ways. The purpose of the model presented is not to act as a method for story construction, which is a creative and skilful endeavour, but to formulate an analogy to the learning process that closely parallels the story–sequence.

According to Reid (1977) and consistent with an extensive literature search, theorists have not related the three–stage structure of stories to cognitive structures. If the structure of stories corresponds to an underlying cognitive structure, then it should be possible to find "structures" in learning theory that correspond to the story structure. Prince's development of the three–stage story structure (1973) is a simple and plausible framework for explaining the construction of stories. With the modified framework of story in hand, one can begin to find parallels between story development and cognitive processes, which would be expected to have significant implications for learning science through stories.

A Model of Conceptual Change

The currently–dominant learning theories in science deal with the phenomenon of conceptual change (Carey 1996; Duit & Treagust, 1998; Macbeth, 2000). Especially constructivist theory, which may be taken as a foundational theory for conceptual change theories, sees learning as the active process of knowledge construction, of which conceptual change is one variety (Duit & Treagust, 1998; Harnad, 1982). In the Conceptual Change Model, initially proposed by Strike and Posner (1982), one mental concept is transformed into another during the process of learning, provided that the self–motivating requirements of intelligibility, plausibility, and fruitfulness are met. The Conceptual Change Model relies primarily on an analogy between the development of science as described by philosophers of science like Kuhn, Lakatos, and Toulmin, and the process of learning science, but it does not describe, in detail, any mental processes that might be involved during conceptual change. Furthermore, the Conceptual Change model was not conceived as a model of the actual learning process, but rather a philosophical framework for determining what should count as good evidence for rational conceptual change. On the other hand, unlike the Conceptual Change Model, the story form could be related to the listener's or reader's mental processes and so illuminate the learning process, itself. And, basic to the story is its three–part temporal structure. So, in order to draw any comparisons to the structure of story, a model of the learning process will need to involve the element of time.

Wandersee (1992) gives a hint as to how conceptual change must be related to the passage of time. He maintains that all cognition is historically situated, a notion that he calls the "historicality" of cognition by which he means that cognition normally operates by comparing to one's present experiences to past experiences. Meaning, according to Wandersee and others (see, for example, Egan, 1989b and Howard, 2000), consists of propositional knowledge that is resident in long–term memory. Consistent with the conceptual change view of learning, the process of meaning–making then consists of comparing new propositional knowledge to knowledge contained in long–term memory. According to conceptual change theory, this process can result in genuine learning only when the new knowledge is close enough to the remembered knowledge to be easily integrated (Carey, 1985; Hewson, 1981; Posner, et al., 1982). What Wandersee does not say explicitly is that the process of learning consists of both meaning–making (gaining understanding) and the integration of the new conceptual structure into long–term memory. This dual characteristic of learning is important since it is possible that material can be understood but not remembered (Howard, 2000, p. 528). In the words of Kieran Egan, "knowledge outside the memory is educationally useless" (1989b, p. 457). Clearly, Egan refers to long–term memory retention as opposed to short–term retention. I would go one step further and claim that inert knowledge, in the sense of Whitehead, without understanding is also educationally useless. The dual nature of learning—understanding and remembering—is fundamental to the development of any model of the learning process and will be taken as one of the basic presuppositions of this thesis.

The view that learning is historically situated is consistent with the view of cognitive psychologists that "the most important variable influencing cognition is the knower's relevant prior knowledge" (Ausubel in Wandersee, 1992, p. 425). Like cognition, the story form is also historically situated, depending on a temporal succession of recorded or recalled events, now in the past. Wandersee speculates that the story format may be more effective in connecting new concepts to remembered concepts than the expository format, but he does not elaborate.

A Temporal Framework for Conceptual Change

Philosopher of science Frank Arntzenius (1995) has proposed a mechanism for conceptual change that is based on the idea that time consists of continuous causal chains, i.e., that time is Markovian. In general, a Markovian process is a seemingly random process in which the likelihood of a state depends only on the immediately preceding state. In applying this idea to the everyday concept of time, Arntzenius means that successive events are recognized by the human mind as though the succeeding event is caused by the immediately preceding event. The idea that sequentially–connected events are likely also causally connected is a natural assumption (Bruner, 1986). Arntzenius argues that learning methodologies or "heuristics" necessarily result from the intuitive Markovian notion of time. Figure 6 is an interpretation of Arntzenius' scheme. Consider that you observe the properties or state of an object, call it the original state. As time passes on,

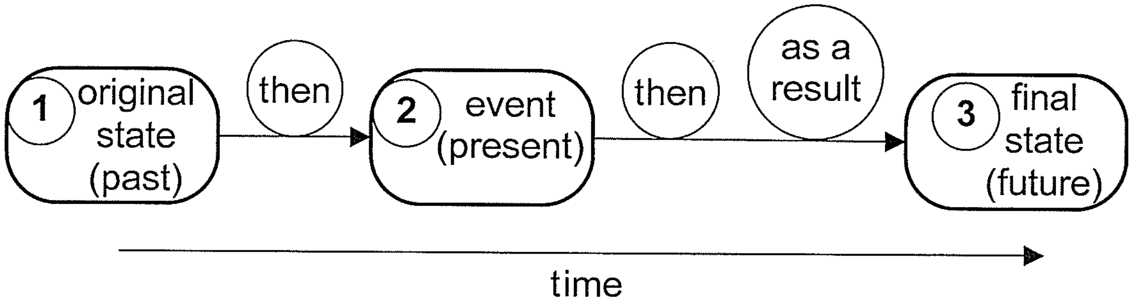


Figure 6: A Temporal Framework for Conceptual Change

passes on, you notice an event involving the object. Then you observe a change in the properties or state of the object. According to Arntzenius, one does not normally assume that the earlier state resulted in the final state without also assuming that it is a result of a change produced by or in the temporally intermediate state. Since you assume that the future depends on the past, you conjecture that you did not know the full state of the object, *otherwise you would have been able to predict the future*, something that Arntzenius does not point out. In other words, the observer naturally concludes that there are unobserved properties of the object that led to the change in state. The need to explain hidden properties, or curiosity, initiates the learning process.

It is possible to relate Arntzenius' temporal framework for conceptual change to cognitive notions of conceptual change. Comparing the "future" to the "past", to use Arntzenius' terms, would involve recalling remembered events or "states". If the "future" differs from the "past", or remembered state, there will be a cognitive disequilibrium, resulting in an innate need to explain, for the reasons given above. This "innate need" is called "explanation–seeking curiosity" by philosopher Eric Schwitzgebel (1999, p. 472).

However, Ohlsson points out that "not knowing the answer to an explanation question is common and normal" (1999, p. 568) and that, by itself, lack of an explanation will not serve as a drive to seek an explanation. In the case of an anomally–driven problem, what is also required, in Ohlsson's view, is a commitment to a particular "theory" that can explain the anomaly. However, not all unanswered questions serve as anomalies for pre–existing or pre–held theories—a theory may first need to be constructed or found to act as an explanation. What I propose as a more general motivating factor is the aspect of engagement—involvement and commitment to task—as it was presented as a part of the Story–Driven Contextual Approach schema of Chapter 4. Provided that there is a sufficient degree of motivation, the student will attempt to construct an explanation for the unanswered question. In terms of our temporal model, the change of state event will need to be explained. Ohlsson (1999) points out that to be able to explain an event, in this sense, is to be able to re–enact the event on the basis of some explanatory mental model:

> To explain an event is to re–enact, in the mind's eye, its genesis. This is done by articulating (Ohlsson, 1992) or *executing* the relevant mental model, a process that gets its name from the analogous process of executing a computer program. The execution reveals the behaviour of the modeled system (under such–and–such conditions). If a model generates a given event, then it explains the event. The relation between explanandum and explanans is re–enactment, not deduction. (Ohlsson, 1999, p. 563)

The notion of explaining as mental re–enactment is important to my presupposition that learning consists of understanding and remembering since understanding will be produced by explanation. The concept of the learning process that is emerging could be expressed as follows: when a sufficient degree of motivation is present and when an suitable explanatory model has been found, unanswered questions about perceived temporal

Story Model	**Learning Sequence**
original state	original state (past)
then	then
action	event (present)
then, as a result	then, as a result
final state	final state (future)

Table 6: Story Model Compared to Learning Sequence

changes, result in a process of mental re–enactment to test for the goodness of the model. If the explanatory model results in a sufficiently good reproduction of the temporal changes, it is accepted as a good explanation. Obtaining elucidation of a problematic event is synonymous with achieving understanding.

Consider now, the remarkable fact that the temporal framework for conceptual change of Figure 6 is identical to the minimal story sequence of Figure 5 with the intermediate state called "event" in Figure 6 and "action" in Figure 5 (see Table 6 for the comparison). Just as the story proceeds temporally from one state through the action and consequently to another state, so, too, the learner observes and remembers the state of an object, the succeeding event involving the object, and the consequent changed state. According to Arntzenius and Schwitzgebel, the unexplained or partially explained change in state would give rise to curiosity or the motivation to explain in the learner. Similarly, in a good story not every detail is told, leaving some to the imagination. In this way, good stories are suspenseful, which, in itself, gives rise to a type of curiosity.

As an example of the temporal framework for conceptual change, the following simple process is proposed, that Ohm may have experienced in formulating his theory:

> *The deflection of the magnetometer on Ohm's apparatus indicated a particular resistance to the flow of electricity,*
> *then a different length wire was inserted into Ohm's apparatus,*
> *and then, as a result, the deflection of the magnetometer on Ohm's apparatus indicated a different resistance to the flow of electricity.*

The process here consists of two experimental observations (states) with an intervention in–between. Experimental intervention usually proceeds in this way. In order to construct a theoretical expression to explain his observations, Ohm wrote an equation that he already had good reason to believe explained the observations. Ohm "replayed" his series of experiments on paper, by first assuming that the current flow through the wires was analogous to the flow of heat, which he understood. As the historical record shows in Ohm's own words (Magie, 1965), Ohm was able to reproduce his experimental results by re–calculating his model with the parameters set at suitable values, showing that his explanation was a good one. This was the justification for his theory. Ohm's method can be viewed as a process of re–enactment of his theoretical expression using suitable parameters that resulted in a reproduction of the experimental observations. Ohlsson's (1999) notion of "explaining as re–enactment" is followed in this particular example. Does this conceptual change sequence also qualify as a story? Clearly, the minimal story sequence, as modified earlier, is followed. However, the usual requirement that a story involve the state of a human or human–like agent is not met. What changes in our case is an experimental observation. Of course, when the subject of explanation is an abstract concept then the involvement of human or human–like agents occurs at a secondary level. It appears, then, that in order to apply our learning structure to a scientific learning situation, the "characters" of the story will sometimes need to be inanimate objects like scientific instruments.

In summary, the modified story framework defines the basic story unit to be a three–stage temporal progression involving human or human–like agents with the final state being caused by the intermediate action on the initial state. The story framework does not exclude any of the other important story characteristics, especially the traits of lifelikeness and affective engagement. Similarly, the temporal conceptual change framework defines a basic learning process to be a three–stage temporal progression involving human or inanimate agents with the final state being caused by an intermediate action on the initial state. For both the story and learning sequence, the initial and final states are related by a simple transformational relationship, with the most common being the inverse relationship. The learning framework depends for its operation on the presence of suitable motivating factors like involvement and commitment to task on the part of the student. Since learning sequences may involve inanimate as well as human agents, the modified story structure must be adapted yet further to account for this fact.

Story as Re–enactment of the Learning Process

What has been argued so far is that the story form consists of a temporal sequence and that at least some learning consists of a similar temporal sequence, along with the formation of long–term memory structures. The story form, then, will be most useful for learning if it becomes a part of the sense–making process and contributes to the formation of long–term memory structures. In Ohlsson's model of sense–making (1999), the learning process includes the re–enactment of remembered events in light of new knowledge. The story form can similarly be viewed as a re–enactment of the cognitive process that would normally be involved in order to learn the story content. The story consists of the recounting of a chronology of events that includes causative links between succeeding events. Remembering, re–telling, hearing, or reading a story will then serve as a form of mental re–enactment.

The structure of a story is just one part of the design of a good story. Other features of stories are, for example, the effect of the untold, suspense, irony, and lifelikeness. These features tend to stimulate the emotions of the reader or listener. But, from the viewpoint of cognitive scientists, "experience arouses emotion, which fixes attention and leads to understanding and insight, which results in [long–term] memory" (Howard, 2000, p. 549). An artistically–crafted story arouses emotions that, in turn, contribute to the integration of the story details with long–term memory. A well–crafted story should, therefore, contribute to better learning of a variety of content knowledge items. But, this is what anthropologists have been telling us all along. In the distant past, stories have been used as the most effective device for passing on the culture to succeeding generations (Levi–Strauss, 1966). In the new context of learning science, the story needs to be "re–invented" to make productive use of this enduring method.

Integration of the Science Story with the Science Storyline

Based on what has been established about the story to be used in teaching science, it is now possible to offer a definition of the "science story" which employs history of science. The science story is defined as *a tightly–knit set of causatively–related chronological episodes taken from the history of science involving the characters' motivations.* The definitions of "science story" as defined here and "science storyline", as defined on page 35, represent two definitive points on a continuum of possible narrative approaches. In specific instances it may be difficult to characterize a particular narrative as either a "science story" or a "science storyline".

A story to be used in the SDCA is rooted in science and history and, therefore, may not contain certain elements commonly associated with the short story genre, like a climax and resolution. The details of the science story are fixed by history and may, in fact, be anti–climactic, especially where scientific efforts have resulted in failure. The science story may not resolve, but may be continued with new science figures in a new setting, even in a different time. The science story seeks to transmit a sense of lifelikeness, whereas the science storyline seeks to impose a degree of coherence on the instructional material. Alternatively, one might say that the science story seeks to arouse interest and focus attention, whereas the science storyline seeks to make linkages among the scientific and historical issues, thereby maintaining a sense of purpose for the instructional sequence. While the science storyline may be "true to life", that is, it is historically factual, it need not be "lifelike", as in the case of the science story where the listener is able to experience, vicariously, the emotions of the characters.

The characteristics of both science storyline and science story are essential to the presentation of an effective story–driven context since they make complementary uses of narrative. The science storyline paints the "big picture", constantly relating the instructional sequence to the underlying historical and scientific issues. The science story engages the emotions of the student and serves to arouse interest and focus attention. The affective context originates primarily with the science story, whereas the historical context, mainly with the science storyline; and the practical, theoretical, and social contexts primarily with the student activities that naturally flow from the other contexts.

Comparison between the LCPA and SDCA

The SDCA presupposes the LCPA. There is nothing in either model that contradicts the other. Stinner's LCPA is constructed on his conception of sound scientific thinking. Based on the nature of science, Stinner introduces his five "contexts of inquiry" that guide his approach to science primarily from a philosophical perspective. These are 1) the foundational questions that guide science, 2) the various methods by which science proceeds, 3) the paradigmatic problems of science (*a la* Kuhn), 4) the justifying experiments of science, and 5) the history of science that encourages students to view scientific developments in the context of their origin and justification. On the other hand, the SDCA proceeds primarily from a pedagogical perspective and employs five contexts of science content and learning. These are the 1) practical, 2) theoretical, 3) social, 4) historical, and 5) affective contexts. In the case of the SDCA, the five contexts serve as an explicit methodology for the design and execution of the learning sequence, whereas Stinner's contexts of inquiry are more implicitly involved in the design of his "storyline" that is to motivate the instructional sequence. The SDCA has an explicit schema that describes the learning process in terms of the contexts, whereas the LPCA does not. Also, the SDCA has a detailed model of the science story to guide its writing, whereas the LCPA does not. The LCPA is primarily meant to serve as a guide for how the instructional unit is *designed*, whereas the SDCA is primarily meant to serve as a specification for how the instructional unit is *taught*, since the pedagogical elements are built into the model.

In the next Chapter, I will present the details of a full–fledged implementation of the Story–Driven Contextual Approach, which proceeds by means of a science storyline with an associated science story.

Chapter 6

IMPLEMENTING THE STORY–DRIVEN CONTEXTUAL APPROACH

Introduction

The discovery of a good story is like the discovery of a hidden treasure. Good historical stories have a fascination all their own. Perhaps the fascination arises from the romance of far–removed events, with participants who had the same kinds of hopes, dreams, and struggles as we, and yet, in a very different environment. As a young child, a frequent request I would make of my father was to hear "stories about long ago". Ever since I began to discover and tell good historical stories myself, I have found that the listeners, too, share my fascination with them. A story that holds great fascination for me and rates as one of the great stories of history is the Atlantic cable story. I came upon this story in 1997 while researching the history of the condenser and searching for the origins of the equations of capacitor charging and discharging. Some of these equations originated with Sir William Thomson, Lord Kelvin, in 1853 (Thomson, 1853). That is when I discovered the story of Kelvin and his major role in the laying of the first trans–Atlantic communications cable and, ever since then, I have not stopped reading about Kelvin and telling the story of the Atlantic cable. Inevitably, when I tell the story, the listeners express great fascination and end up re–telling the story to others.

The Atlantic cable story not only includes narrative elements that are intrinsic to a good science story—high adventure, heroism, and scientific ingenuity—but it also contains scientific and mathematical concepts that beg scientific inquiry. Kelvin, himself, expressed considerable enthusiasm over the nature of the theoretical problems involved. In an 1857 letter to Helmholtz, Kelvin wrote:

> I have worked a good deal … at the solution of problems (exactly like those of Fourier) regarding the propagation of electricity through submarine wires. It is the most beautiful subject possible for mathematical analysis. No unsatisfactory approximations are required; and every practical detail, such as perfect insulation, resistance in the exciting and receiving instruments, differences between the insulating power of gutta–percha and the coating of tow and pitch round it, mutual influence of the different conductors …, attempts to send messages in both directions at the same time, gives a new problem with some interesting mathematical peculiarity. (in Thompson, 1910, pp. 336–337)

Students with some physics and mathematics background easily comprehend both the practical and theoretical problems raised by the cable and there are a large number of such issues. Among the scientific problems raised are 1) the theory of electrical signals in a long co–axial cable, 2) the influence of material purity on the resistivity of copper, 3) the calculation of resistance of a wire, 4) the calculation of capacitance of a co–axial cable, 5) the nature of a signal in a simple capacitor–resistor circuit as a simplification of (1), 6) the density of sea–water and buoyancy, and 7) the nature of the forces on a cable released into the ocean. With such an abundance of material for generating scientific problems, it is interesting that a literature search reveals that, apparently, nothing has yet been published about the Atlantic cable story that relates to its instructional use in a science classroom setting even though it has such great potential to be used in science instruction.

It was this realization that prompted me to develop a historical–scientific story to capture the students' imagination and thereby enhance the students' learning experience. As I began to develop the theoretical framework (see Chapters 4 and 5), the opportunity to test the model arose. Testing the theoretical framework would ideally require a class with enough background physics knowledge to capitalize on the mathematical and experimental physics topics encapsulated in the episode. Both theoretical and experimental investigations would need to be carried out by students. Recent developments in my department vis–à–vis laboratory work presented the ideal situation for testing the framework. Since advanced student laboratories, to a certain degree, reflect the kinds of research going on in my department, and since we have strong theoretical and experimental components, it has become commonplace to have both theoretical and experimental investigations in the student laboratory. Furthermore, stand–alone laboratory courses have recently been created, adding an even greater degree of flexibility to the kinds of activities that students might initiate in these courses. Against this background, I planned and executed my framework in a fourth–year physics laboratory in the winter of 2001. The advanced laboratory presents an ideal environment for testing a new theoretical model in science education. Student cooperation is high and there are few distracters from the planned activities. Flexibility of instruction is also higher in higher–level courses, so that there are few limitations beyond scheduling for implementing any kind of activity. The advanced laboratory class of that year had four students. Since the study of selected aspects of advanced electromagnetism using advanced mathematics is one of the laboratory topics I wish to teach, the history of the development of the first Atlantic cable naturally presented itself as a story that provides the context for various electrical investigations. However, the problems that had to be solved by Lord Kelvin, the main scientific consultant for the Atlantic cable project, ranged well beyond the electrical aspects, including the design of measuring instruments and cable dynamics, to mention just two. As I had personally found the Atlantic cable story engaging and stimulating, I assumed that this would also be the case for my students.

Since my primary objective was to develop the theoretical framework for incorporating history of science in science teaching, testing of student responses within its implementation assumed a secondary role. However, as a teacher, I am constantly seeking to improve my instructional methods, and as I engaged in the instructional activities associated with the Story–Driven Contextual Approach, I recorded any relevant anecdotal material that arose spontaneously.

Providing Students with the Context

The instructional sequence began with the presentation of the science storyline which is a history of science case study written in such a way as to abide by the story model just developed. The writing of the science storyline was the culmination of several years of reading about the Atlantic cable story, telling it to people, and writing about it. In order to create as rich a context as possible by making diverse connections, I included reference to current–day Atlantic cables in the case study. As my theoretical framework assumes an important role for affective arousal during a teaching–learning sequence, I considered it essential to include in the case study a science story which, unlike the case study itself, is able to include creative literary elements like suspense and verisimilitude. I constructed the science story from two published eye–witness accounts of the same events during one of the cable–laying voyages in 1858 (Thompson, 1910, pp. 361–363; Bright, 1903, pp. 119–121). The accounts are intertwined in such a way as to make sense chronologically. Excerpts from the accounts were used in their entirety. A small number of minor details, consistent with the historical record, were added in order that the reader or listener could make sense of the story. For instance, the historical fact that Kelvin developed his own version of the Wheatstone bridge around 1855 and used it as a standard electrical testing device was used to explain some of the cable testing in the story. In addition, the fact that unreliable batteries with a mixture of sand and electrolyte were sometimes used at the time and that they were later found to have been the cause for specific problems in signal transmission across the cable, was included in the conclusion to the story. In the story, reproduced below, all additions or changes from the original sources are enclosed in square brackets. As these additions are consistent with the historical record, they may be considered as historical interpretation rather than fictionalized history.

The teacher's role, that of storyteller, is critical in this initial stage. Based on the importance of the storytelling approach, I chose to make a verbal presentation of the Story–Driven Context, at the narrative "level" of both science story and storyline, and accompanied it with PowerPoint for the sake of including any diagrams and pictures. I made the verbal presentation before giving any other explicit information to the students. The following section presents the science storyline and story exactly as I told it to my students. My presentation was also video–taped by a student from another class who volunteered for the task.

The Story of Lord Kelvin and the Atlantic Cable

On August 17, 1858, intercontinental electronic communication officially began with a ninety–eight–word message from Queen Victoria to American president James Buchanan across the first Atlantic cable. The transmission of the message took more than sixteen hours to complete. However, the cable promised to be able to work at about twenty words per minute if the problems that plagued the developers could be resolved. These revolved around the design of the cable, quality control in its manufacture, and the design and appropriate use of testing equipment for its use. The leading scientific figure in the cable–laying mission was the mathematical physicist Professor William Thomson, later to become Lord Kelvin, and referred to as Kelvin here. He worked with financiers, engineers, and "electricians" to make the cable a reality. The term "electrician" was used, in the nineteenth century, to refer to anyone working with electricity in an experimental sense. The laying of the first functioning Atlantic cable between 1857 and 1866 is an epic story. It involved high drama—suspense and life–risking adventure. The success of the mission was made possible only through the solution of a wide range of scientific and technological problems.

The main scientific question surrounding the design and practicality of an Atlantic cable was conceived at a meeting of the British Association in London in 1854 in the form of a chance question asked of Kelvin after the presentations had been made. Kelvin recalls the incident:

> I was hurriedly leaving the meeting of the British Association, when a son of Sir William Hamilton, of Dublin, was introduced to me with an electrical question. I was obliged to run away to get a steamer by which I was bound to leave for Glasgow, and I introduced him to Professor Stokes, who took up the subject with a power which is inevitable when a scientific question is submitted to him. He wrote to me on the subject soon after that time, and some correspondence between us passed, the result of which was that a little mathematical theory was worked out, which constituted, in fact, the basis of the theory of the working of the submarine cable. (Thomson, 1890, p. 486)

Little did the thirty–year–old professor know that the problem would become an all–consuming one for him and that the he would have a major role in the laying of the first communications cable linking Britain and North America – a cable that was known for a time as the Eighth Wonder of the World (Kimmel and Foster, 1866).

The basic technology and physics of the first successful Atlantic cable remained in place for nearly one hundred years. By the year 1900 there were 19 transatlantic cables in operation (Canso Historical Society, 2001). However, until 1956, the fastest transatlantic communication possible was by means of telegram, which had to be hand–delivered to the recipient from the telegraph office. It was only in 1956 that the first telephone cable was completed, providing voice communications between London and New York or Montreal, which, up to that point, where provided by radio signals. The cable was installed by a British, Canadian, and American consortium in a mammoth three–year effort and consisted of 35 high–quality telephone circuits (Arthur C. Clarke Foundation, 2001). Then the development of the physics and technology of optical fibres made possible the laying of a transatlantic fibre–optic cable by 1988 (Hecht, 1999). By 1997 the growth rate of data traffic on undersea cables was ninety percent per year and there were 186,000 miles of undersea cable (Treese, 1998). Today, intercontinental cable laying is a large multi–national business on the part of many corporations, who install and service optical fibre cables as a part of the world–wide web.

Kelvin's direct involvement in the Atlantic cable venture began in 1856 when he met American tycoon Cyrus Field. Field had retired with a fortune at age 33 but re–entered the business world as a result of the Atlantic cable project having caught his imagination. It would probably not have been possible to complete the successful laying of a working Atlantic cable between 1857 and 1866 had it not been for this combination of genius. Field possessed future vision, eternal optimism, dogged persistence, and business prowess. Kelvin possessed an international reputation as a scientist, new insights into the physics of the cable, an unfailing dedication to the project, and an unwavering confidence in the answers supplied by science. Of the directors selected for the Atlantic Cable Company in 1856, Kelvin was the only scientist. By 1848, he had proposed the absolute (or Kelvin) scale of temperature. In 1854, he had begun the first in a series of papers relating to cable telegraphy. That same year he was awarded his first patent for "Improvements in electrical conductors for telegraphic communication" (Thompson, 1910, p. 1275). The year that the Atlantic Cable Company was formed, he was awarded the Royal Medal of the Royal Society. In the light of these accomplishments and of their timing, it is not surprising that Kelvin was invited to become a member of the board of the Atlantic Cable Company.

However, before the venture began several areas of study had to be developed, among them oceanography. Up to that point, the ocean floor had not been mapped and in anticipation of the Atlantic cable, methods of depth sounding had to be invented. One of the key questions that preoccupied scientists involved in the Atlantic cable venture was signal delay in a submarine cable of the length required in the distance between Valentia Bay, Ireland and Trinity Bay, Newfoundland, around 2400 miles (3900 km). Samuel Morse, inventor of the Morse code, another consultant to the project, wrote in 1856 that "the perceptible retardation of the electric current … threatened to perplex our operations, and required careful investigation before we could pronounce with certainty the commercial practicability of the Ocean Telegraph" (Dibner, 1959, pp. 20–21). On this issue, Kelvin disagreed with others. Faraday and Morse were convinced that the signal delay depended only on the capacitance of the cable, but, based on work he had already done, Kelvin argued that the signal delay depended on the product of the cable resistance and capacitance. Kelvin's conclusions were that since both the resistance and capacitance are proportional to the cable length, if the cable length is doubled then the signal evolution will be four times as long; hence, the solution to the problem at hand is clear. The insulation thickness of the cable must be increased to decrease the capacitance and the conductor thickness must be increased to decrease the resistance. The dependency of the amount of signal delay on the square of the cable length became known as Kelvin's "doctrine of squares" (Dibner, 1959, p. 47). In Kelvin's time, his theoretical explanation was a scientific controversy. In 1855, the project electrician on the Atlantic cable, Mr. Whitehouse, had published a paper disputing Kelvin's theory based on his measurements. The exchange between Kelvin and Whitehouse became a public debate. Kelvin showed, in his response, that Whitehouse had misinterpreted his own measurements.

When Kelvin joined the Atlantic cable venture, it was already too late for the cable design to be altered. Since he believed the cable resistance to be an important factor, he began testing sample pieces of the cable as it was manufactured. He found that among 45 samples he tested, the conductivity varied from 42% to 102% of the standard copper sample he used (Dibner, 1959, p. 17). He maintained, in his dealings with the Atlantic Cable Company, that measures be taken to insure the purity of the copper conductor during its manufacture.

The process of the laying of the first fully successful Atlantic cable consisted of several short failed attempts and five major attempts, two of which were successful. Kelvin was aboard every voyage as an unpaid scientific consultant. These voyages were made from 1857 to 1866, with the American Civil War intervening between the third and fourth expeditions. The third expedition, which began on July 28, 1858 and ended on August 5, resulted in successful communication for a period of 27 days, but thereafter the cable failed gradually, until, by October 20, it was completely silent.

The cable–laying missions began in 1857 by using two ships provided by the British and American governments. The British ship was the *Agamemnon* and the American ship the *Niagara*. That year mission failures prevailed from August 5 to 11, until on August 11, when the ships were over 200 miles out, the cable broke due to the accidental misapplication of the cable brake that was used to keep the cable from paying–out in an uncontrolled fashion. There was no more time for another expedition that year due to the shortness of the storm–free period on the north Atlantic.

In order to improve signalling capability over the cable, Kelvin invented a mirror galvanometer, which was called the marine galvanometer. The galvanometer consisted of a tiny steel magnet attached to an equally tiny mirror suspended from a silk fibre. The suspension was placed inside a fine copper coil. The mirror reflected a beam of light originating from a lamp placed behind a slit on a measuring scale. If the room was darkened, the reflected spot of light could be observed on the measuring scale. The letters of the alphabet were transmitted as certain amounts of deflection on the scale or as positive and negative deflections to represent Morse code. The marine galvanometer was capable of measuring a current as small as 10^{-11} Ampere (Jewkes, 2002). The invention of the marine galvanometer was seen as very significant at the time. Maxwell was inspired to write several stanzas of poetry, a parody on Tennyson's song III from *The Princess*, which appeared in *Nature* May 16, 1872. The first stanza is quoted here:

> The lamplight falls on blackened walls,
> And streams through narrow perforations;
> The long beam trails o'er pasteboard scales,
> With slow, decaying oscillations.
> Flow, current, flow! Set the quick light–spot flying!
> Flow, current, answer, lightspot! Flashing, quivering, dying. (Quoted in Dibner, 1959, p. 27)

This is an example of how the scientific advances and discoveries surrounding the Atlantic cable inspired the population of Britain and America. The venture received much attention, not only from the scientific community, but from the press and the community at large.

A major difficulty plaguing the venture was the struggle to maintain the mechanical integrity of the cable. A restraining force had to be applied as the cable was released and the ship moved forward so that the immense weight of cable extending downward to the ocean floor did not cause the cable to be released (or "paid–out" in Kelvin's terms) uncontrolled and simply end up in coils on the ocean floor. The measures taken to keep this from happening had prematurely ended the attempts in the first year. In the intervening months, Kelvin not only constructed his mirror galvanometer, but worked out the dynamics equations for the motion of the cable during its release into the water, showing that it behaved like a concatenary, making a perfectly straight line from the point of entry into the water to the ocean floor. The model allowed the developers to make more accurate tension calculations for the cable.

An Eyewitness Account

The next year, in 1858, the ships set sail again only to be met with a severe storm, the worst in living memory, in which the *Agamemnon*, carrying Kelvin, almost sank. Finally, on July 29 of that year, after a number of failures and false starts, the ships met in mid–Atlantic and again began laying the cable. A member of the crew recorded the events of the evening of July 29 as follows:

> *July 29, [1858, aboard the Agamemnon]*—it is rather an exciting occupation to watch the tell–tale signals [on the Professor's galvanometer as the cable] pays out. Even the most indifferent "holds his breath for a time", when their story is of dubious or ominous import. [The Professor and the electricians] are regarded by the engineers about the paying–out machinery as birds of evil omen. If one of their number rushes upon deck or approaches with a hurried step, they look as a Roman husbandman

might have done at a crow on a blasted tree. Indeed, it is almost impossible to realize the anxiety and *heart–interest* everybody manifests in the undertaking. No one seems to breathe freely. Few, but the crew, even sleep soundly. Professor Thomson frequently does not put off his clothes at night.

To–night, but a few hours after starting, there was an alarming crisis. The *Agamemnon* had signaled to the *Niagara,* "Forty miles submerged," and she was just beginning her acknowledgment, when suddenly, at 10 P.M., communication ceased. According to orders, those on duty sent at once for Dr. Thomson. He came in a fearful state of excitement. The very thought of disaster seemed to overpower him. His hand shook so much that he could scarcely adjust his eyeglass. The veins on his forehead were swollen. His face was deadly pale. [He spoke as if to himself: "I shall have to use the bridge arrangement of Professor Wheatstone"]. Mr. Bright, the chief electrician, had noticed the Professor hurrying to the electrical room, and followed close on his heels. He supposed the fault might lie in a suspicious portion, which had been observed in the main coil. Not a moment was lost by Mr. Canning, the engineer on duty, in setting electricians to work to cobble up the injury as well as time would permit, for the cable was going out at such a rate that the damaged portion would be paid overboard in less than twenty minutes, and former experience had shown that to check either the speed of the ship or the cable would, in all probability, be attended by the most fatal results. Just before the lapping was finished, Professor Thomson [completed making his test and reported that the Wheatstone bridge indicated a wire resistance consistent with the fault being on board the ship.] Attention was naturally directed to the injured piece as the probable source of the stoppage, and not a moment was lost in cutting the cable at that point with the intention of making a perfect splice.

Not a second was to be lost, for it was evident that the cut portion must be paid overboard in a few minutes; and in the meantime the tedious and difficult operation of making a splice had to be performed. The ship was immediately stopped, and no more cable paid out than was absolutely necessary to prevent it breaking. As the stern of the ship was lifted by the waves a scene of the most intense excitement followed. It seemed impossible, even by using the greatest possible speed, and paying–out the least possible amount of cable, that the junction could be finished before the part was taken out of the hands of the electricians. The main hold presented an extraordinary scene. Nearly all the officers of the ship and of those connected with the expedition stood in groups about the coil, watching with intense anxiety the cable as it slowly unwound itself nearer and nearer the joint, while the electricians worked at the splice as only persons could work who felt that the life and death of the expedition depended upon their rapidity. But all their speed was to no purpose, as the cable was unwinding within a hundred fathoms; and, as a last and desperate resource, the cable was stopped altogether, and for a few minutes the ship hung on by the end. Fortunately, however, it was only for a few minutes, as the strain was continually rising above two tons and it would not hold on much longer. When the splice was finished the signal was made to loose the brakes, and the repaired section of cable passed overboard in safety.

When the excitement, consequent upon having so narrowly saved the cable, had passed away, we awoke to the consciousness that the case was yet as hopeless as ever, for the electrical continuity was still entirely wanting. To the consternation of all, the electrical tests applied seemed to indicate the fault to be overboard, and in all probability some fifty miles from the ship. [However, Professor Thomson warned that this indication could also be caused by a faulty battery aboard the *Niagara* not sending an appreciable current.]

[As a result of the doubt expressed by Professor Thompson] it was determined to keep the cable slowly going out, that all opportunity might be given for resuscitation. The scene in and about the electrical room was such as those present shall never forget. The two clerks on duty, watching, with the common anxiety depicted on their faces, for a propitious signal; Dr. Thomson, in a perfect fever of nervous excitement, shaking like an aspen leaf, yet in mind clear and collected, testing and waiting, with half–despairing look for the result; Mr. Bright, standing like a boy caught in a fault, his lips and cheek smeared with tar, biting his nails as if in a puzzle, and looking to the Professor for advice; Mr. Canning, grave, but cool and self–possessed, like a man fully equal to such an emergency; the captain, viewing with anxious look the bad symptoms of the testing as indicated on the galvanometer and pointed out by Dr. Thomson. Behind, in the darker part of the room, stood various officers of the ship. Round the door crowded the sailors of the watch, peeping over each other's shoulders at the mysteries, and shouting "gangway!" when any one of importance wished to enter. The eyes of all were directed to the instruments, watching for the slightest quiver indicative of life. Such a scene was never witnessed save by the bedside of the dying. Things continued thus. Dr. Thomson and the others left the room, convinced they were once more doomed to disappointment. Still the cable went slowly out. The clerks continued sending regular currents. All at once the galvanometer indicated a complete breaking in the water. All made the dread interpretation, and looked at each other in silence. Suddenly one sang out, "Haloa! the spot has gone up to 40 degrees." The clerk at the measuring instrument bolted right out of the room, scarcely knowing where he went for joy; ran to the deck, and cried out, "Mr. Thomson! the cable's all right; we got a

> signal from the *Niagara*." In less than no time he was down, tested, found the old dismal result, and left immediately. He had not disappeared in the crowd when a signal came which undoubtedly originated in the *Niagara.* The joy was so deep and earnest that it did not suffer any to speak for some seconds. But when the first stun of surprise and pleasure passed, each one began trying to express his feelings in some way more or less energetic. Dr. Thomson laughed right loud and heartily. Never was more anxiety compressed into such a space of time [and never was there more relief. The entire incident of signal failure] lasted exactly one hour and a half, but it did not seem a third of that time.
>
> [Later, it was confirmed that the *Niagara* had been using an unreliable sand battery and had replaced it with Daniell's cells. What would we have done, had it not been for the Professor and his galvanometer]? (adapted from Thompson, 1910, pp. 361–363 and Bright, 1903, pp. 119–121)

The Mission Continues

It was found that the *Niagara*'s compass was reading wrongly due to the large amount of iron in the sheath of the cable coiled in its holds. This caused it to veer off course badly. A pilot ship was sent in front of the *Niagara* to keep it on course. Communication along the cable was kept from ship to ship during the entire process, using coordinated electrical signals measured by Kelvin's marine galvanometer, to insure that the cable remained intact. On August 5, the ships reached their respective destination ports with their cables. For the first time in history, a telegraphic message was sent across the Atlantic, linking North America with Europe.

The announcement of the success met with weeks of jubilant public celebration across North America. Comparisons of this event were made to the discovery of America and the invention of printing. In the meantime, Kelvin had left the cable installation to pursue his regular duties. The electricians setting up communications under the direction of Whitehouse found that, contrary to Whitehouse's instructions, they needed to use Kelvin's marine galvanometer in order to detect signals. Whitehouse had his own detection system that he wished to use, but it did not work. He ordered the operators to fabricate signals on his own signal detection system manually and record them as if they had arrived across the cable. The fact that the cable was not a complete success was hidden from the public. The signals were detected with the mirror galvanometer using a candle as a light source. Three operators traced the beam reflection on a wall and made a majority guess as to the intended character that was being transmitted. During this time the ongoing disagreement between Whitehouse and Kelvin came to a climax as Whitehouse insisted on increasing the signal strength from 600 to 2000 Volts, which resulted in the cable's insulation failing on September 18. After this fiasco, the Atlantic Telegraph Company dismissed Whitehouse. Soon the state of affairs of the communications was realized by the press and on September 26 of that year the *New York Leader* printed the question; "Have we a pack of asses among us and are they specially engaged in electrical experiments over the Atlantic cable?" The newspaper question showed insight into the situation, since the developers were, in fact, using the installation process to develop the techniques needed.

Since the failure caused a financial loss of at least £500,000 (at least the equivalent of $200 million CDN, today) for the investors, there was a great public outcry and the British Board of Trade, together with the Atlantic Cable Company, appointed a commission of inquiry into the matter, which deliberated from December 1, 1859, to September 4, 1860. The report issued was comprehensive and explicit in its recommendations for what should be done to insure success. After that, with substantial effort, Field was able to raise another £600,000 to attempt to install an improved Atlantic cable. The largest ship in the world at the time was the *Leviathan*, now idle, having failed financially. The ship weighed 19,000 tons and was powered by an 11,500 horsepower steam engine (the equivalent of 75 average automobile engines). The company manufacturing the cable purchased the ship, renamed it the *Great Eastern* and refitted it for the task at hand. The task of coiling the 2300 miles of cable into three holding tanks took from January to June of 1865. A crew of 500 was required to operate the ship, of which 200 were required merely to raise its anchor as it left port on July 23, 1865. This attempt to lay the cable was full of problems, and finally, on August 2 the cable broke after 1,186 miles had been laid. Numerous attempts to snag the cable and lift it off the ocean floor failed, and on August 11 the ship headed back to port.

Surprisingly, the level of optimism about the venture remained as high as ever. A new company, the Anglo–American Telegraph Company, had been formed, and commissioned the manufacture of more new cable of greater tensile strength than that of the previous year. As the *Great Eastern* sailed from Ireland on July 13, 1866, it maintained communication with the shore via the new cable. It arrived off the shore of Newfoundland on July 27. A signal was sent from Newfoundland to Ireland using a miniature homemade battery consisting of a copper gun cap, a tiny strip of zinc, and one drop of salt water. The initial speed of operation was eight words per minute and the cost of transmitting a message of twenty words or less was $100 U.S. in gold or $150 U.S. in banknotes.

As a result of his role in the laying of the Atlantic cable, Queen Victoria knighted Kelvin in 1866. The success was met with universal praise and celebration. As an example of the reactions, one could take what was written by the physicist Joseph Henry: "This is a celebration such as the world has never before witnessed. It is not alone to commemorate the achievements of individuals, or even nations, but to mark an epoch in the advancement of our common humanity" (Dibner, p. 158). Kelvin was justifiably honoured by British society. In 1892, Queen Victoria raised Sir William to the peerage, which is when he became Lord Kelvin. When he died in 1907, Kelvin was buried in Westminster Abbey next to Sir Isaac Newton.

Analysis of the Story–Driven Context

The first step in validating the Story–Driven Context Approach would be to see if it reflects the minimal story model. Several examples will be drawn.

The entire story begins for Kelvin when a student asks him a question about the characteristics of electrical signals in long submarine cables (Thomson, 1890, p. 486). The minimal story sequence can be composed as follows

> *A student asked Kelvin how a signal would propagate down a very long cable,*
> *and then Kelvin realized he did not clearly understand the answer,*
> *and then, as a result, Kelvin worked out his theory of signal dynamics.*

The implicit state pair here is not knowing–knowing, with the understanding that this is an idealization. However, Kelvin only comes to the realization of not knowing after being prompted by the student's question. Kelvin's involvement with the venture began with the issue of cable manufacture. The story–sequence can be constructed as follows:

> *Kelvin believed that the cable was unable to sustain a signal across the Atlantic*
> *and copper cables had inconsistent electrical resistance,*
> *and then Kelvin formulated his doctrine of squares,*
> *and then, as a result, cable manufacturers used better quality control to manufacture the cable,*
> *and then, as a result, the cable was capable of sustaining a signal across the Atlantic.*

Here, the story sequence consists of a compound story with two nested story sequences and the state pair is frustrated–successful. Another significant event in the presentation is Kelvin's invention of the marine galvanometer:

> *It was technologically unfeasible to lay an Atlantic cable,*
> *and then Kelvin invented the marine galvanometer,*
> *and then, as a result, the cable venture was successful.*

Again, the state pair is frustrated–successful.

The included story, which is a first–hand account, has two main minimal stories. These are

> *The crew was unable to obtain a signal,*
> *and then Kelvin oversaw the cable's testing and repair,*
> *and then, as a result, the crew was eventually able to obtain a signal.*

and

> *The crew was still unable to obtain a signal,*
> *And then Kelvin refused to give up hope but kept the cable paying out,*
> *And then, as a result, when the signal re–appeared, the crew was able to obtain a signal.*

Both examples exhibit the state pair frustrated–successful. The last minimal story is slightly more complex with the action (Kelvin refused to give up hope but kept the cable paying out) actually being a minimal story in itself.

The story model has proven to be useful in testing case studies (science storylines) for their story–likeness, as can be seen in the examples above. It is important to insure that historical case studies are not simply chronologies, but that they exhibit genuine story–structure characteristics. As for the science story, it is naturally expected to exhibit the story–structure as entailed by the story model and so the story model is not the critical test for the science story. A more critical test is whether the science story is effective in portraying literary characteristics of a story, which give rise to affective responses. Student responses to the story, reported below in the section on the affective context, will bear directly on the effectiveness of the science story.

The Instructional Plan

Although students did not know anything about the Atlantic cable story when they came to my presentation, they did know that they would be responsible for finding various practical and theoretical problems to address. The presentation of the Story–Driven Context was attended not only by my class, but by a sizable number of other students who were invited. During the presentation I showed the students their "Atlantic cable"—a co-axial cable about 300 meters long (see Figure 7). At the end of my presentation, I gave students a copy of my presentation, two original papers by Kelvin (see Appendix A for the second of the two), a re–construction of Bright's (1898) adaptation of Kelvin's theory (see Appendix B), and a number of supplementary materials (see Table 7 for a complete list). Students were expected to read the materials and at the next class discuss their questions and ideas about problems they might like to pursue. This class was called the "stu-

Original Papers

Thomson, 1853; Thomson, 1865 (see Appendix A); Bright, 1898, pp. 528-535 (see Appendix B)

Supplementary Materials

Copy of Instructor presentation
Specifications for the 1858 and 1866 Atlantic Cables (see Appendix C)
Quick Kelvin Facts (see Appendix D)

Laboratory Materials and Equipment

Coil of RG58 coaxial cable, approximately 300 meters long
Two BNC coaxial patch wires with alligator clips
Terminating resistors and alligator clips
Multimeter for measuring resistance, capacitance, and inductance
Pulse generator
Oscilloscope

Table 7: Instructional Materials

dent proposal seminar". I found that students were not yet ready to begin investigations after the proposal seminar, since they were still in the process of formulating ideas and gaining understanding of the issues. The next class was called the "project initiation seminar". In this seminar I introduced several experimental methods, such as risetime measurements, along with brief demonstrations. Students asked final questions and then organized themselves into groups and planned their investigative activities. For the investigative component, I supplied the simulated "Atlantic cable", professional quality test equipment (see Figure 7), and various computer resources, including Mathcad, Maple, Excel, and PowerPoint. The activities were self–scheduled by the students and I was available for consultation at times when they worked on them. After students had completed much of their work we had a planning meeting. The purpose was to find out if anything was left to be done and to plan how students would make their final report,

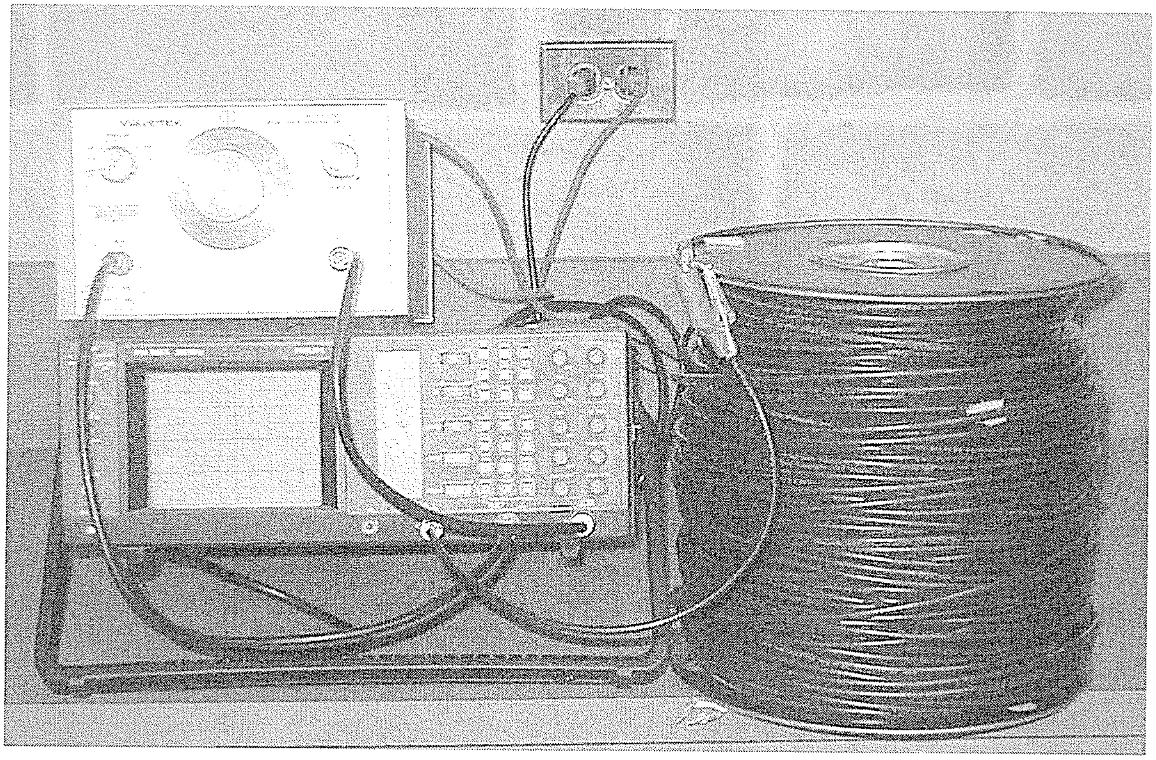
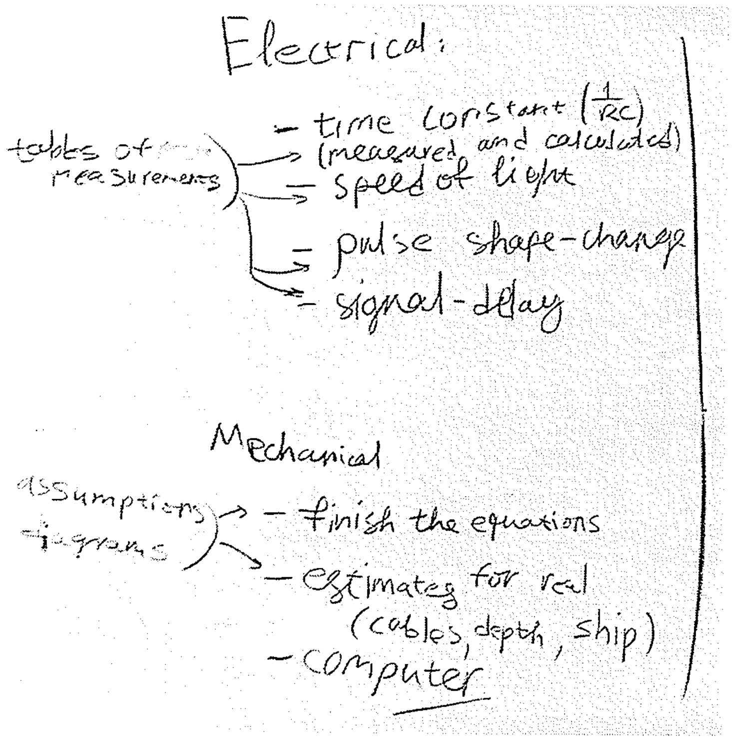


Figure 7: Experimental Equipment

which was in the form of a formal public presentation with each student responsible for a difference 10–minute segment. Part of the meeting was chaired by one of the students who listed the required tasks on the whiteboard. See Figure 8 for a photograph of that list. The presentations were graded (see Appendix E) and after that students submitted laboratory books containing their notes, records, calculations, and graphs, which were also graded.



Electrical:

tables of measurements

- time constant ($\frac{1}{RC}$) (measured and calculated)
- speed of light
- pulse shape-change
- signal-delay

Mechanical

assumptions
diagrams

- finish the equations
- estimates for real (cables, depth, ship)
- computer

Figure 8: Student Task List

Results on Implementing the Story–Driven Contextual Approach

Since the teaching of the Story–Driven Context did not comprise a formal study, I kept only brief anecdotal notes of spontaneous items that I observed during the natural course of instruction and I took a few photographs. Throughout the exercise, the various responses were overwhelmingly positive. However, positive responses, by themselves, will not provide information useful in assessing the Story–Driven Contextual Approach. Any evaluations will need to be criterion–referenced. Therefore, student responses and activities will be referenced to the five contexts of the approach—the practical, theoretical, social, historical, and affective contexts.

An important additional feature of the Story–Driven Contextual Approach that surfaced in its use in my classroom was that each student was free not only to pursue problems that reflected his or her own predisposition but also his or her ability level. Some students selected problems that others would have considered too challenging.

The Practical Context

Students pursued their practical investigations with a significant degree of enthusiasm, since they had initiated the tasks themselves. Working in groups, students designed experiments to measure electrical characteristics (resistance, capacitance, inductance, and signal risetime) that also required knowledge of the length of the cable. The investigation was made more interesting owing to the length of the cable which had to be unwound many times around the perimeter of a large room in order to measure the characteristics with the cable uncoiled. Measuring the length directly was a challenge that students met in a very systematic manner. Two students carefully placed a string of known length (a few meters) alongside the cable and then moved one end of the string to match up with the other end, allowing them to begin matching the next length segment. Another student pressed a counter each time this was done and the fourth student watched the procedure carefully so there was no miscount. Students concluded that they might have devised a more efficient method of measuring the length after spending more than an hour on the length measurement alone. They had a good laugh over the procedure when it occurred to them how comical their actions appeared to visitors to the room.

The Theoretical Context

Some students chose to investigate the dynamics of the cable as it was being paid–out from the ship. As there was no means for a practical investigation, some students chose to use data which was provided by Kelvin in one of his original papers (Thomson, 1865) and to work out a mathematical model based on Kelvin's proposal. Other students chose to work out the equations for the electrical characteristics of the cable and compare them to measurements. They chose this route because they had recently covered these topics in their electromagnetism course. In either case, the interaction between the "experimentalists" and "theoreticians" demonstrated the give and take between theory and experiment in the development of science. That some students naturally have a proclivity to become theoreticians and others to become experimentalists became obvious at this point. Later, when it came time to report on their work, students had to correlate their results, showing them how experimentalists and theoreticians communicate in the course of "doing science".

The Social Context

Each problem, experimental or theoretical, was attempted by at least two students and some by all students in the class. Those working on the same question were required to work together toward a common solution. The reporting on the students' work was done by means of a multi–part, public, oral presentation made to the entire department, both faculty and students. Good cooperation was required in order to make a good presentation. Students were expected to depend on each other, as well as on their instructor, for answers to problems. In this manner, students not only benefited from an enhanced learning environment, as suggested by Vygotsky, but they practised "getting along" in a setting where the efforts of one student affected the mark of another. "Getting along" in groups, or engaging in a cooperative effort, is valuable in producing a scientific attitude.

The social context is, perhaps, the most difficult of the five—the practical, theoretical, social, historical, and affective—for students to engage in. Competition among students, difficulties in scheduling common times, and natural differences in personalities are factors that generally mitigate against cooperation, and students tend to work on their own as much as possible. However, the assignment of a common final presentation proved especially useful in motivating cooperation. Also, I found that if students are given the opportunity to work out differences on their own, when the instructor is not looking over their shoulders, cooperation is more easily achieved.

The Historical Context

Students had been given three original papers—two by Kelvin and one interpreting Kelvin's theory—to read in order to assist them in formulating the questions and problems they would investigate. One of the papers was entirely understandable to the students; the other, however, seemed to be at the limit of their mathematical ability and they found it too challenging. In future, this paper would need to be gone through with the students in a traditional blackboard lecture format in order to clarify the mathematical

dynamometer: A device for measuring the tension on the cable as it was released.
grapnel: A form of grappling hook used to snag a cable from the ocean bottom.
gutta–percha: An early form of rubber used for insulation of wires.

Table 8: Some Definitions

steps. Students returned from their first reading of the historical materials asking the meaning of some terms: “grapnel”, “gutta–percha”, and “dynamometer” (see Table 8). After I had explained the terms and several issues had been discussed, students re–read the papers and one remarked “I am reading the articles for a second time and this time they make much more sense”. The historical details and associated science story were the key ingredients of the context since they gave students a sense of the purpose for studying various related questions and topics. Without them, the effectiveness of the approach would have been lost. Students expressed their fascination with the story. None of them had heard it before. One remarked, “It’s great!” In the first seminar, I asked students for their reactions to the science storyline and story and what about it they had liked the most. They listed the poem, the personal details about scientists, the fascination with “old facts” they had not known before, the fact that the cable was rated as the eighth wonder of the world, and the “sense of panic” in the story which was rated as “very good”. One student wished to pursue the etymology of the term “gutta–percha” since it sounded exotic. A student requested a copy of the complete Maxwell poem, of which one stanza was quoted in the science storyline. As I had expected, well–told and carefully selected history can serve as a significant motivator for students.

The Affective Context

During the course of being immersed in the Story–Driven Context, I observed indicators of a number of emotions like amusement, expectation, enthusiasm, and satisfaction that I had not observed in students during traditional instruction that involved blackboard lectures and cook–book style laboratories. In response to the Maxwell poem, one student remarked, “This is the first poem I have ever heard that I liked!” The affective context pervades the other contexts, since an emotional response in any other context connects that context to the affective context. For instance, the degree of enthusiasm for the historical elements of the science storyline and the degree of satisfaction upon completing difficult experimental and theoretical tasks and presenting them publicly demonstrated the function of various activities in the affective realm at the same time as they operated in the historical, theoretical, experimental, or social context.

Summary

While the contexts are all inextricably connected in the learning process, it is the science storyline that provided the impetus for learning in each context. In this respect the framework met expectations. A further test for the Story–Driven Context schema (see Figure 4) would be whether a) all five contexts are actually relevant and important in the process and b) whether any other contextual factors appear that should have been taken into account. Initial indications are that, indeed, all five contexts play a prominent role in the learning process as envisioned by the Story–Driven Context Approach. No other contextual factors have arisen during the exercise. However, as in any exercise of theory development, observations are driven by theoretical considerations, and, if the theory is reasonably good, major mismatches between expectations and observations are not expected. The question of whether a greater amount of conceptual and content knowledge was learned during the process is more difficult to establish. Subjective indications based upon informal discussions with students show that they *believe* they learn more in the Story–Driven Context Approach compared to traditional instruction. Further experimental investigations of the Story–Context Approach at this level will be affected by the small degree of quantitative reliability afforded by the small number of students, however they need to include consideration of the practical, theoretical, social, historical, and affective contexts. In the meantime, the approach has demonstrated significant value in promoting a more enjoyable, richer, learning experience.

Chapter 7

DISCUSSION, RECOMMENDATIONS, AND CONCLUSION

Theoretical Considerations

The purpose of my thesis, as summarized in the title, is to develop a theoretical framework for the inclusion of history of science in science teaching. As in the development of any theory, the issue of what real–world observations can be tied in to the theory must, of necessity, arise. The tension between theory and observation is effectively illustrated in the famous discussions between Heisenberg and Einstein. Gerald Holton has again discussed this issue, recently. He writes:

> The following year, 1926, is one of high drama in this growing but troubled relationship. In April, Heisenberg gave a two–hour lecture on his matrix mechanics before von Laue's famous physics colloquium at the University of Berlin. In the audience, with a whole group of potentates, was Einstein. It was their second meeting. Einstein, interested and no doubt disturbed by the lecture, asked Heisenberg to walk home with him—there is that walk again—and thus ensued a remarkable discussion, which Heisenberg later reconstructed and reported in many places, from 1969 on.
>
> At that encounter, Heisenberg once more tried to draw attention to having not dealt with unobservable electron orbits inside atoms, but with observable radiation. He reports having said to Einstein: "Since it is acceptable to allow into a theory only directly observable magnitudes, I thought it more natural to restrict myself to these, bringing them in, as it were, as representatives of electron orbits." To this Einstein is said to have responded, "But you don't seriously believe that only observable magnitudes must go into a physical theory?" Heisenberg goes on, "In astonishment, I said: I thought that it was exactly you who had made this thought the

> foundation of your relativity theory. … Einstein replied: Perhaps I used this sort of philosophy; but it is nevertheless nonsense (*Unsinn*)." And then came Einstein's famous sentence: "Only the theory decides what one can observe." (Holton, 2000)

In educational theory, this kind of tension also exists. As I pointed out in Chapter 3, learning is an unobservable that must be evaluated by proxies, such as tests. However, the reliability of test results in determining what has been learned is a highly problematic issue (Klassen, 1999). In a sense, learning is to educational theory what electron orbits were to early quantum theory. What kinds of things qualify as "learning" is also partly dictated by the descriptive model or philosophy that one adopts for learning. In my work on theory development, it has become clear that my model of learning considers the learning process as consisting of meaning–making (or gaining understanding) *and* integration of this understanding with long–term memory structures (see Chapter 5, especially page 117, for a discussion of this). Learning is facilitated by the presence of appropriate contexts that relate either to the concepts or skills to be learned or to the ways in which learning is made possible. From the cognitive perspective, contexts are a parallel concept to brain pathways and complexes that are constructed as learning takes place. Besides the obvious theoretical justification for placing an emphasis on contexts, these also lend themselves much more readily to observable phenomena. Everyday, observable entities are associated with the contexts—student practical work, theoretical problem solutions, group dynamics, teacher stories of historical origin, and affective expression. In Heisenberg's terms, the contexts are analogous to "observable radiation". A question that naturally arises at this point is whether activities in the various contexts could replace tests as observable evidence of learning. This is an important question to which I shall return, later.

Embarking on any research project in education, in addition to the overall objective, traditionally requires the asking of research or foundational questions. I argued in Chapter 3 that asking such questions during the process of theory development may be of limited usefulness, as theory development is a dynamic and creative process. In fact, such questions may need, at some point, to be revised. At this point, however, I would like to re–state the two foundational questions posed in Chapter 3 and see to what extent they have been satisfied.

> *1. What contextual model of instruction at the middle or upper university level lends itself to effective teaching and significant learning?*
>
> *2. What model of story accurately reflects major aspects of narrative theory and captures the essential features that make it an effective teaching device?*

The first question requires the development of a contextual model of instruction and that was the subject of Chapter 4. It is clear from the results reported in Chapter 6 that the model lends itself to implementation in upper university years. Would the model also lend itself to middle level university? The only factors that are different here are the preparation of students and the somewhat larger class sizes. With the selection of a context in which the concepts are developed at an appropriate mathematical and conceptual difficulty, this should not present a problem. Furthermore, there is no less flexibility in scheduling at this level, and, with an appropriate amount of planning, the scheduling should also be possible. Although the model has been tested in the upper university year there is reasonable indication that it should be equally applicable at the middle level.

The concepts of "Effective teaching and significant learning" in Question 1 go hand–in–hand even though constructivist educational theory sheds doubt on a direct causative link between teaching and learning. Learning is seen as a personal constructive activity in which the role of the teacher is to provide the appropriate environment and conceptual and cognitive resources in which learning may readily take place. The important question here is whether evidence of student engagement with the five contexts also serves as evidence of learning having taken place. Clearly, if the constructivist idea is taken seriously, then the observation of activities that are normally identified with effective learning is evidence of learning having taken place. And, if one takes seriously the significant problems of interpretation of test scores, a logical conclusion would be that the assessment of contexts is better evidence of learning than tests. At this point, the conclusion that evidence of activities in the various contexts may serve as evidence of learning should be taken tentatively only, since the issues raised in possibly replacing test scores are too controversial to be accepted on the basis of a single argument, no matter how logical. Nevertheless, a major test of the theoretical framework is whether an evaluation of the contexts and the student activities in the contexts will serve as a more reliable indicator of long–term learning than traditional factual tests.

Further issues that arise in the context of Foundational Question 1 are the use of more direct test–like assessment of learning and the formation of long–term memory structures as suggested by the view of learning taken in this thesis. However, these issues also arise in Foundational Question 2. Question 2 requires the development of a dual–aspect model for story and learning. This was the subject of Chapter 5. First, the model must be a reflection of major narrative theory, and this has been achieved in the adoption and modification of a structuralist model of story. The model of Prince was chosen partly for its simplicity and because it reflects the temporal formation of learning structures. The success of the story model, which was developed in Chapter 5, in representing the underlying structure of simple historical science stories has been manifestly demonstrated in Chapters 5 and 6. The model is one simple way of assuring that historical stories are not merely chronologies but that they also contain causal or intentional elements. Significant in my model is the relaxation of the requirement that the beginning and ending of the three–part story structure must be related as binary opposites. Instead, I require that the relation be a simple transformation of the initial story element into the final story element. Simple (and suitable) transformational operations on the initial story state are accepted. The binary opposite relationship (A as compared to not–A), albeit the most important one, is simply one type of transformational relationship. Based on my reading of the literature, this aspect of my modified story model is original. The other modification to the story model that I make, which is also made by Egan and implied by Bruner, is that inanimate "characters" be allowed.

Also original to my rendition of the story model is its linkage to a temporal model of conceptual change. In extending the story model to incorporate a learning model, I have taken the temporal conceptual change heuristic of Frank Arntzenius (1995), shown how it is identical to the story structure, and extended Arntzenius' description of the learning process according to the view of Ohlsson (1999). The result is an original hybrid story–learning model that shows considerable value in its explanatory power in various simple learning sequences. Learning is viewed as a process of re–enactment of problematic events in the light of some available explanatory "theory". It is interesting to note that this view is consistent with the use of an abductive theory selection method (a la Peirce), like that which has been promoted by Anton Lawson (2002). In one version of abductive inference, observations are "allowed" to suggest a theory by selecting among various plausible candidates for the best one. For instance, the Ohlsson learning model would contend that when novices observe the motion of objects, they replay in their minds what would be the resulting motion if there were an internal motive force in the object. The explanation reproduces the observed motion fairly well, and for novices, *since this is the simplest available explanation*, it causes them to opt for an impetus–like "theory" of motion.

Beyond merely explaining simple learning sequences, my purpose was to develop a model for the effectiveness of stories to engender significant *long–term* learning. This aspect of effective learning is the most difficult to evaluate. Long–term retention of knowledge is rarely assessed, since it is difficult to locate students years after the original instance of learning. Knowledge about long–term memory is still in the development stages; but, some facts are known. For instance, it is known that "once a memory link is formed, there is a short period, of perhaps hours to days, during which the responsible cellular changes can reverse. Then the cellular changes become permanent." (Alkon, 1992, p. 208). Thus, the nature of a large–scale learning module, such as the Story–Driven Contextual Approach, reinforces the forming of permanent memory structures by having the student return to the problems several times over a period of a number of weeks. It is also known that the "strength" of memory structures depends on the circumstances surrounding their initial formation. Factors like deliberate intention, difficulty of task, and affective engagement assist in forming memory complexes that less easily disintegrate over the short–term (Howard, 2000). In this regard, what we do know about memory supports the approach taken by the Story–Driven Contextual Approach. It appears that the way to assess the success of the Story–Driven Contextual Approach in terms of its support for long–term memory is to assess its consistency with well–established knowledge of memory formation and retention.

The last aspect of the model to be considered here is its usefulness in generating good assessments of student learning in the traditional sense. One of the student activities, as reported in Chapter 6, is to present a formal verbal report on their investigations and conclusions. This type of activity, although not entirely traditional, in the teaching of science especially, does serve as a kind of "test". An issue to consider is to what extent this might serve as evidence of having gained understanding of various concepts or methods. Coming to an understanding is a process of explanation as described by Ohlsson (1999). Ohlsson claims that the process of explanation in one of re–enactment, rather than one of deduction (see Chapter 5 for a discussion of this). Students re–enact or execute an explanatory model for their observations to see if it produces the observed results. It is easy to connect the final student presentation to this view. Students construct a kind of "story" in describing their investigations and theories, and how they came to their conclusions. The preparations for the talk and the talk itself can be seen as a type of re–enactment, itself a part of the learning process. When students make their final presentation, they have constructed conceptual models that satisfy their activities and observations. The presentation thus serves as a suitable ending to the learning sequence that began with the telling of a story.

Each aspect of the two foundational questions has been addressed by the thesis. Still at issue is whether the theoretical framework could become a legitimate theory candidate in education. As was discussed above, the models do have testability. Some tentative predictions have also been made in the discussion. However, legitimacy must be established over time and include the process of dissemination and peer review.

Another aspect to consider is whether the eight standards for theory development as outlined in Chapter 3 have also been met. In summary, these standards dictate that theoretical statements must be free of contradiction, free of ambivalence, communicable, abstract, general, precise, parsimonious, and conditional (Markovsky, 1996, p. 33). It could be argued that critics of the theoretical framework must apply tests like these, but a brief evaluation of the standards will be made here. The first three standards are met by clear and logical communication of the framework, which this thesis has set out to achieve. The quality of abstractness requires that the statements not be bound to specific instances, but that they have a degree of generality. This will be achieved if the methods described can be used in settings different from the example of Chapter 6. The models certainly describe methods that are not bound to the example given. Furthermore, the framework has precision in that it can be used to design large–scale teaching units like that described in Chapter 6 and to analyse real story sequences. The seventh condition is that of simplicity. This condition cannot be tested in practice unless other theory candidates that apply to the same phenomena can be found. The last condition, that of conditionality, was met in Chapter 3 where foundational assumptions and delimitation were specified. Furthermore, the models apply to a defined concept of learning applied to the use of stories in contexts. Examples from the history of science show that a new theory often languishes without broad acceptance until it can capture the imagination of the research community through the dramatic confirmation of a bold prediction. An example is the bold prediction of geologists Lawrence Morley and Fred Vine in 1963 that magnetic properties of rocks show certain alternating patterns in accordance with plate tectonic theory. The confirmation of that prediction in 1965 was unexpected and precipitated a rapid shift in theory–commitment in geology at the time. It is possible that the theoretical framework, upon further refinement, might make a "prediction" about the usefulness of contexts in the assessment of student performance.

Criticisms of the Historical Story Approach

There are criticisms that can be made of the basic assumption of the value of the historical approach and of the use of stories to portray history. In the first place, there is always the criticism that by including history in the presentation of science, curriculum content will be sacrificed. However, there is a certain presupposition behind this criticism. Based on the logical argument that if studying two topics is better than learning one, and so on, it seems that "as many topics as possible, at all costs" is the best approach to the curriculum. However, this kind of a logical extension takes no account of the learning process and what, of all the information presented, the student will even be able to recall having studied after a year or two. The argument over whether breadth is better than depth in learning really presents a false dilemma. As shown in the contextual approach, breadth and depth can *both* be achieved through the designing of a sufficiently large and diversely–connected context. The question of coverage of the field is different. With the exponential growth of knowledge, it is becoming a meaningless argument that a particular field of study should be "covered". Instead, students should learn, in as great a depth as they are able, as many topics as can be introduced in the time available. The objective is to engender learning that will, at least to some extent, be long–term. This view of what is to be taught could, perhaps, be called *sustainable learning*—learning at a pace that investigates topics to enough depth to maintain student interest and with enough good pedagogical methods to engender significant learning. Thus, since there is sufficient evidence that the historical approach has pedagogical value, this argument alone is sufficient to include history.

A second criticism I would like to consider is the so–called problem of presenting history in story form. It is argued that creative stories have an ending that is not pre–determined, but, that historical stories have endings that are determined by the historical record, and, thus, they can never raise interest like fictional stories. Science stories have endings that are determined by scientific facts, it is argued, and hold little or no suspense for students. Kuhn makes a particularly damming comment on the use of history in science when he writes that "because science students 'know the right answers,' it is particularly difficult to make them analyse an older science in its own terms." (1962/1996, p. 167).

I would like to reply to this criticism on two accounts. In the first place, students have rarely heard historical stories beforehand and so they do not know the outcome. For them, the story has as much suspense as a fictional story. Furthermore, I argue that historical stories have an element that gives them an advantage over fiction. Students know that the lifelikeness is not just imagined, but it corresponds to real people and events that happened long ago. As demonstrated in Chapter 6, history holds a significant fascination for students. The same argument holds for historical science stories. Students are still fascinated by stories of discovery in the light of unexpected difficulties despite the fact that they already know about the phenomena in terms of textbook science. It is not the outcome but the process that is important. Knowing the outcome is thus not a deterrent to engagement. This is manifestly clear in the story of Kelvin and the Atlantic cable. Everyone knows Kelvin was instrumental in the laying of the cable, or at least they infer it when the science storyline is begun. This, in no way, detracts from the excitement, suspense, and adventure inherent in the story of how Kelvin got to the point of establishing successful communications. However, it cannot be denied that the stories do have greater effectiveness if they are told at the beginning of units, rather than at the end, or, better still, as a running story that unfolds the creation of scientific theories and the discovery of confirming or disconfirming phenomena. In terms of presenting discarded theories, it is not so obvious that students are as sceptical as Kuhn would have us believe. Both in my own experience, and in that of others I have talked to, students are always engaged in history as long as it is presented appropriately. I contend that in order for serious criticisms of the historical approach to be sustained, the presuppositions about learning must be substantially different from currently–accepted theory and few pedagogical alternatives are being considered.

A final criticism I would like to consider is the contention that, although the contextual approach with a science storyline is a good idea, the science story is dispensable. Whether the science story is considered an essential component depends on the philosophy of learning and the related understanding of the learning process. If understanding *and* long–term memory is the goal, then the factors that are likely to support the formation of long–term memory structures must be considered. This is the main reason that the science story is considered important. It is for the reasons of motivation and memorability that the science story is included and even though these elements can be provided to a certain extent by the science storyline and contexts, they are, with good reason, expected to be significantly enhanced by the science story.

Significance

The significance of this thesis lies in the degree to which the theoretical framework can answer the dilemma that is being experienced in science education with respect to the use of history of science. I argued in Chapter 3 that the approaches to incorporating history of science in science teaching are in a pre–paradigmatic state. The main reason for this, I argued, lies in the lack of a unifying theory that will dictate the development of instructional materials to be used. My purpose has been to develop a theory that incorporates both aspects of the presentation method of history, namely the science story and elements of learning theory. This objective has been met and, beyond my initial expectations, I also found an opportunity to test the models in a real classroom situation. The test of the model has provided a significant, although preliminary, degree of support for the model. Lastly, as in any scholarly work, significance lies in its claim to originality. This aspect has already been firmly established in the preceding sections of this Chapter.

Recommendations

The recommendations for future development relate to the role of the framework as a theory–candidate. First, an instrument to test the presence of significant student activity in all five contexts should be designed and tested. Second, the theoretical framework must be disseminated to a wider audience where it may be subjected to more scrutiny. At that point the framework may need to be adjusted and predictions and tests can be formulated. Lastly, the researching, gathering, and writing of historical contexts and science stories according to the Story–Driven Contextual Model is required for making a significant contribution to science classroom instruction. These could be the subject of a conference or of an international consortium of contributors like has been done for the International Pendulum Project.

Conclusion

I conclude by referring, first, to the meaning of history and its relation to science and then to its relation to story. R. G. Collingwood (1945) has argued that history is a more fundamental form of thought than science. He writes that

> the scientist who wishes to know that … an event has taken place in the world of nature can know this only by consulting the record left by the observer and interpreting it, subject to certain rules, in such a way as to satisfy himself that the man whose work it records really did observe what he professes to have observed. This consultation and interpretation of records is the characteristic feature of historical work. … I conclude that natural science as a form of thought exists and always has existed in a context of history, and depends on historical thought for its existence. (pp. 176–177)

What Collingwood describes about scientific work appears very much like the process of historiography. Scientific records exclude the human dimension of the work that brought about certain scientific conclusions or theories in science. In that sense, science is a specialized rational reconstruction of history. Perhaps it would not be an exaggeration to say that science has become a form of dehumanized and decontextualized history. The only way to interest young students in science is to portray it differently—more realistically from the human and contextual perspective. Practical, theoretical, social, historical, and affective contexts enter into each effective learning situation. The objective of humanizing science through its history is implicit in my development of the Story–Driven Contextual Approach. Furthermore, this approach is effective because it makes use of innate features of learning. Likely, Whitehead (1929) pinpointed part of what is innate in learning when he points out that all of learning is based on a cycle of romance, precision, and generalization. In the case of the Story–Driven Contextual Approach, the romance is portrayed in beginning the sequence with the science storyline and story. The stage of precision is gained by students when they tackle difficult problems. Generalization is achieved when students summarize their results, compare them to the results of the others, and present their conclusions to a wider audience. The stage of romance should not be underemphasized at any student level, since it entails the affective aspects that produce learning that is more likely to last. Similarly, the stage of generalization produces a type of motivation that also contributes to long–term learning. However, at the core of all these considerations is the story–form. In the words of educators Nel Noddings and Carol Witherell,

> we learn from stories. More important, we come to understand—ourselves, others, and even the subjects we teach and learn. Stories engage us. … Stories can help us to understand by making the abstract concrete and accessible. What is only dimly perceived at the level of principle may become vivid and powerful in the concrete. Further, stories motivate us. Even that which we understand at the abstract level may not move us to action, whereas a story often does. (1991, pp. 279–280)

Given that stories aid understanding, cause engagement, and produce motivation, and even help us to understand ourselves—all essentials of learning—given that the narrative form also enhances retention and long–term memory, and given that models of learning are so closely aligned with the model of the Story–Driven Contextual Approach, the use of the science story in science teaching can, indeed, become a heuristic teaching device that is not only attractive, but also self–sustaining.

Appendix A

ON THE FORCES CONCERNED IN THE LAYING AND LIFTING OF DEEP–SEA CABLES

PROCEEDINGS

OF THE

ROYAL SOCIETY OF EDINBURGH.

VOL. V. 1865–66. No. 69.

Monday, 18*th December* 1865.

SIR DAVID BREWSTER, President, in the Chair.

At the request of the Council, Professor William Thomson of Glasgow delivered the following Address on the Forces concerned in the Laying and Lifting of Deep-Sea Cables.

THE forces concerned in the laying and lifting of deep submarine cables attracted much public attention in the years 1857–58.

An experimental trip to the Bay of Biscay in May 1858, proved the possibility, not only of safely laying such a rope as the old Atlantic cable in very deep water, but of lifting it from the bottom without fracture. The speaker had witnessed the almost incredible feat of lifting up a considerable length of that slight and seemingly fragile thread from a depth of nearly 2½ nautical miles.* The cable had actually brought with it safely to the surface, from the bottom, a splice with a large weighted frame attached to it, to prevent untwisting between the two ships, from which two portions of cable with opposite twists had been laid. The actual laying of the cable a few months later, from mid ocean to Valencia on

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* Throughout the following statements, the word mile will be used to denote (not that most meaningless of modern measures, the British statute mile) but the nautical mile, or the length of a minute of latitude, in mean latitudes, which is 6073 feet. For approximate statements, rough estimates, &c., it may be taken as 6000 feet, or 1000 fathoms.

one side, and Trinity Bay, Newfoundland, on the other, regarded merely as a mechanical achievement, took by surprise some of the most celebrated engineers of the day, who had not concealed their opinion, that the Atlantic Telegraph Cumpany had undertaken an impossible problem. As a mechanical achievement it was completely successful; and the electric failure, after several hundred messages (comprising upwards of 4359 words) had been transmitted between Valencia and Newfoundland, was owing to electric faults existing in the cable before it went to sea. Such faults cannot escape detection, in the course of the manufacture, under the improved electric testing since brought into practice, and the causes which led to the failure of the first Atlantic cable no longer exist as dangers in submarine telegraphic enterprise. But the possibility of damage being done to the insulation of the electric conductor before it leaves the ship (illustrated by the occurrences which led to the temporary loss of the 1865 cable), implies a danger which can only be thoroughly guarded against by being ready at any moment to back the ship and check the egress of the cable, and to hold on for some time, or to haul back some length according to the results of electric testing.

The forces concerned in these operations, and the mechanical arrangements by which they are applied and directed, constitute one chief part of the present address; the remainder is devoted to explanations as to the problem of lifting the west end of the 1200 miles of cable laid last summer, from Valencia westwards, and now lying in perfect electric condition (in the very safest place in which a submarine cable can be kept), and ready to do its work, as soon as it is connected with Newfoundland, by the 600 miles required to complete the line.

Forces concerned in the Submergence of a Cable.

In a paper published in the "Engineer" Journal in 1857, the speaker had given the differential equations of the catenary formed by a submarine cable between the ship and the bottom, during the submergence, under the influence of gravity and fluid friction and pressure; and he had pointed out that the curve becomes a straight line in the case of no tension at the bottom. As this is always the case in deep-sea cable laying, he made no farther reference to the general problem in the present address.

When a cable is laid at uniform speed, on a level bottom, quite straight, but without tension, it forms an inclined straight line, from the point where it enters the water, to the bottom, and each point of it clearly moves uniformly in a straight line towards the position on the bottom that it ultimately occupies.* That is to say, each particle of the cable moves uniformly along the base of an isosceles triangle, of which the two equal sides are the inclined portion of the cable between it and the bottom, and the line along the bottom which this portion of the cable covers when laid. When the cable is paid out from the ship at a rate exceeding that of the ship's progress, the velocity and direction of the motion of any particle of it through the water are to be found by compounding a velocity along the inclined side, equal to this excess, with the velocity already determined, along the base of the isosceles triangle.

The angle between the equal sides of the isosceles triangle, that is to say, the inclination which the cable takes in the water, is determined by the condition, that the transverse component of the cable's weight in water is equal to the transverse component of the resistance of the water to its motion. Its tension where it enters the water is equal to the longitudinal component of the weight (or, which is the same, the whole weight of a length of cable hanging vertically down to the bottom), diminished by the longitudinal component of the fluid-resistance. In the laying of the Atlantic cable, when the depth was two miles, the rate of the ship six miles an hour, and the rate of paying out of the cable seven miles an hour, the resistance to the egress of the cable, accurately measured by a dynamometer, was only 14 cwt. But it must have been as much as 28 cwt., or the weight of two miles of the cable hanging vertically down in water, were it not for the frictional resistance of the water against the cable slipping, as it were, down an inclined plane from the ship to the bottom, which therefore must have borne the difference, or 14 cwt. Accurate observations are wanting as to the angle at which the cable entered the water; but from measurements of angles at the stern of the ship, and a

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* Precisely the movement of a battalion in line changing front.

dynamical estimate (from the measured strain) of what the curvature must have been between the ship and the water, I find that its inclination in the water, when the ship's speed was nearly $6\frac{1}{2}$ miles per hour, must have been about $6\frac{3}{4}°$, that is to say, the incline was about 1 in $8\frac{1}{2}$. Thus the length of cable, from the ship to the bottom, when the water was 2 miles deep, must have been about 17 miles.

The whole amount (14 cwt.) of fluid resistance to the motion of this length of cable through it, is therefore about ·81 of a cwt. per mile. The longitudinal component velocity of the cable through the water, to which this resistance was due, may be taken, with but very small error, as simply the excess of the speed of paying out above the speed of the ship, or about 1 mile an hour. Hence, to haul up a piece of the cable vertically through the water, at the rate of 1 mile an hour, would require less than 1 cwt. for overcoming fluid friction, per mile length of the cable, over and above its weight in water. Thus fluid friction, which for the laying of a cable performs so valuable a part in easing the strain with which it is paid out, offers no serious obstruction, indeed, scarcely any sensible obstruction, to the reverse process of hauling back, if done at only 1 mile an hour, or any slower speed.

As to the transverse component of the fluid friction, it is to be remarked that, although not directly assisting to reduce the egress strain, it indirectly contributes to this result; for it is the transverse friction that causes the gentleness of the slope, giving the sufficient length of 17 miles of cable slipping down through the water, on which the longitudinal friction operates, to reduce the egress strain to the very safe limit found in the recent expedition. In estimating its amount, even if the slope were as much as 1 in 5, we should commit only an insignificant error, if we supposed it to be simply equal to the weight of the cable in water, or about 14 cwt. per mile for the 1865 Atlantic cable. The transverse component velocity to which this is due may be estimated with but insignificant error, by taking it as the velocity of a body moving directly to the bottom in the time occupied in laying a length of cable equal to the 17 miles of oblique line from the ship to the bottom. Therefore, it must have been about 2 miles in $17 \div 6\frac{1}{2} = 2{\cdot}61$ hours, or ·8 of a mile per hour. It is not probable that the actual motion of the cable lengthwise through the water can affect this result much. Thus, the *velocity of settling* of a horizontal piece of the cable (or velocity of sinking through the water, with weight just borne by fluid friction) would appear to be about ·8 of a mile per hour. This may be contrasted with longitudinal friction by remembering that, according to the previous result, a longitudinal motion through the water at the rate of 1 mile per hour is resisted by only $\frac{1}{17}$th of the weight of the portion of cable so moving.

These conclusions justify remarkably the choice that was made of materials and dimensions for the 1865 cable. A more compact cable (one for instance with less gutta percha, less or no tow round the iron wires, and somewhat more iron), even if of equal strength and equal weight per mile in water, would have experienced less transverse resistance to motion through the water, and therefore would have run down a much steeper slope to the bottom. Thus, even with the same longitudinal friction per mile, it would have been less resisted on the shorter length; but even on the same length it would have experienced much less longitudinal friction, because of its smaller circumference. Also, it is important to remark that the roughness of the outer tow covering undoubtedly did very much to ease the egress strain, as it must have increased the fluid friction greatly beyond what would have acted on a smooth gutta percha surface, or even on the surface of smooth iron wires, presented by the more common form of submarine cables.

The speaker showed models illustrating the paying-out machines used on the Atlantic expeditions of 1858 and 1865. He stated that nothing could well be imagined more perfect than the action of the machine of 1865 in paying out the 1200 miles of cable then laid, and that if it were only to be used for *paying out*, no change either in general plan or in detail seemed desirable, except the substitution of a softer material for the "jockey pulleys," by which the cable in entering the machine has the small amount of resistance applied to it which it requires to keep it from slipping round the main drum. The rate of egress of the cable was kept always under perfect control by a weighted friction brake of Appold's construction (which had proved its good quality in the 1858 Atlantic expedition) applied to a second drum carried on the same shaft with the main drum. When the weights were removed from the brake (which could be done almost instantaneously by means of a simple mechanism), the resistance to the egress of the cable, produced by "jockey pulleys," and the friction at the bearings of the shaft carrying the main drum, &c., was about $2\frac{1}{2}$ cwt.

Procedure to Repair the Cable in case of the appearance of an electric fault during the laying.

In the event of a fault being indicated by the electric test at any time during the paying out, the safe and proper course to be followed in future (as proved by the recent experience), if the cable is of the same construction as the present Atlantic cable, is instantly, on order given from an authorised officer in the electric room, to stop and reverse the ship's engines, and to put on the greatest *safe* weight on the paying-out break. Thus in the course of a very short time the egress of the cable may be stopped, and, if the weather is moderate, the ship may be kept, by proper use of paddles, screw, and rudder, nearly enough in the proper position for hours to allow the cable to hang down almost vertically, with little more strain than the weight of the length of it between the ship and the bottom.

The best electric testing that has been practised or even planned cannot show within a mile the position of a fault consisting of a slight loss of insulation, unless both ends of the cable are at hand. Whatever its character may be, unless the electric tests demonstrate its position to be remote from the outgoing part, the only thing that can be done to find whether it is just on board or just overboard, is to cut the cable as near the outgoing part as the mechanical circumstances allow to be safely done. The electric test immediately transferred to the fresh-cut seaward end shows instantly if the line is perfect between it and the shore. A few minutes more, and the electric tests applied to the *two ends* of the remainder on board, will, in skilful hands, with a proper plan of working, show very closely the position of the fault, *whatever its character may be.* The engineers will thus immediately be able to make proper arrangements for resplicing and paying out good cable, and for cutting out the fault from the bad part.

But if the fault is between the land end and the fresh-cut seaward end on board ship, proper simultaneous electric tests on board ship and on shore (not hitherto practised, but easy and sure if properly planned) must be used to discover whether the fault lies so near the ship that the right thing is to haul back the cable until it is got on board. If it is so, then steam power must be applied to reverse the paying-out machine, and, by careful watching of the dynamometer, and controlling the power accordingly (hauling in slowly, stopping, or veering out a little, but never letting the dynamometer go above 60 or 65 cwt.), the cable (which can bear 7 tons) will not break, and the fault will be got on board more surely, and possibly sooner, than a "sulky" salmon of 30 lbs. can be landed by an expert angler with a line and rod that could not bear 10 lbs. The speaker remarked that he was entitled to make such assertions with confidence now, because the experience of the late expedition had not only verified the estimates of the scientific committee and of the contractors as to the strength of the cable, its weight in water (whether deep or shallow), and its mechanical manageability, but it had proved that in moderate weather the Great Eastern could, by skilful seamanship, be kept in position and moved in the manner required. She had actually been so for thirty-eight hours, and eighteen hours during the operations involved in the hauling back and cutting out the first and second faults, and reuniting the cable, and during seven hours of hauling in, in the attempt to repair the third fault.

Should the simultaneous electric testing on board and on shore prove the fault to be 50 or 100 or more miles from the ship, it would depend on the character of the fault, the season of the year, and the means and appliances on board, whether it would be better to complete the line, and afterwards, if necessary, cut out the fault and repair, or to go back at once and cut out the fault before attempting to complete the line. Even the worst of these contingencies would not be fatal to the undertaking with such a cable as the present one. But all experience of cable-laying shows that almost certainly the fault would either be found on board, or but a very short distance overboard, and would be reached and cut out with scarcely any risk, if really prompt measures, as above described, are taken at the instant of the appearance of a fault, to stop as soon as possible with safety the further egress of the cable.

The most striking part of the Atlantic undertaking proposed for 1866, is that by which the 1200 miles of excellent cable laid in 1865 is to be utilised by completing the line to Newfoundland.

That a cable lying on the bottom in water two miles deep can be caught by a grapnel and raised several hundred fathoms above the bottom, was amply proved by the eight days' work which followed the breakage of the cable on the 3d of August last. Three times out of four that the grapnel was let down, it caught the cable, on each occasion after a few hours of dragging, and with only 300 or 400 fathoms more of rope than the 2100 required to reach the bottom by the shortest course. The time when the grapnel did not hook the cable it came up with one of its flukes caught round by its chain; and the grapnel, the short length of chain next it, and about 200 fathoms of the wire-rope, were proved to have been dragged along the bottom, by being found when brought on board to have interstices filled with soft light gray ooze (of which the speaker showed a specimen to the Royal Society). These results are quite in accordance with the dynamical theory indicated above (see Appendix II.), according to which a length of such rope as the electric cable, hanging down with no weight at its lower end, and held by a ship moving through the water at half a mile an hour, would slope down to the bottom at an angle from the vertical of only 22°; and the much heavier and denser wire-rope that was used for the grappling would go down at the same angle with a considerably more rapid motion of the ship, or at a much steeper slope with the same rate of motion of the ship.

The only remaining question is: How is the cable to be brought to the surface when hooked? The operations of last August failed from the available rope, tackle, and hauling machine not being strong enough for this very unexpected work. On no occasion was the electric cable broken.* With strong enough tackle, and a

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* The strongest rope available was a quantity of rope of iron wire and hemp spun together, able to bear 14 tons, which was prepared merely as *buoy-rope* (to provide for the contingency of being obliged, by stress of weather or other cause, to cut and leave the cable in deep or shallow water), and was accordingly all in 100 fathoms-lengths, joined by shackles with swivels. The

hauling machine, both strong enough, and under perfect control, the lifting of a submarine cable, as good in mechanical quality as the Atlantic cable of 1865, by a grapnel or grapnels, from the bottom at a depth of two miles, is certainly practicable. If one attempt fails, another will succeed; and there is every reason, from dynamics as well as from the 1865 experience, to believe that in any moderate weather the feat is to be accomplished with little delay, and with very few if any failing attempts.

The several plans of proceeding that have been proposed are of two classes—those in which, by three or more ships, it is proposed to bring a point of the cable to the surface without breaking it at all; and those in which it is to be cut or broken, and a point of the cable somewhat eastward from the break is to be brought to the surface.

With reference to either class, it is to be remarked that, by lifting simultaneously by several grapnels so constructed as to hold the cable without slipping along it or cutting it, it is possible to bring a point of the cable to the surface without subjecting it to any strain amounting to the weight of a length of cable equal to the depth of the water. But so many simultaneous grapplings by ships crossing the line of cable at considerable distances from one another would be required, that this possibility is scarcely to be reckoned on practically, without cutting or breaking the cable at a point westward of the points raised by the grapnels. On the other hand, with but three ships the cable might, no doubt, be brought to the surface at any point along the line, without cutting it, and without subjecting it at any point to *much* more strain than the weight corresponding to the vertical depth, as is easily seen when it is considered that the cable was laid generally with from 10 to 15 per cent. of slack. And if the cable is cut at some point not far westward of the westernmost of the grapnels, there can be no doubt but it could be lifted with great ease by three grapnels hauled up simultaneously

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wire and hemp rope itself never broke, but on two of the three occasions a swivel gave way. On the last occasion, about 900 fathoms of Manilla rope had to be used for the upper part, there not being enough of the wire buoy-rope left; and when 700 fathoms of it had been got in, it broke on board beside a shackle, and the remaining 200 fathoms of the Manilla, with 1540 fathoms of wire-rope and the grapnel, and the electric cable which it had hooked, were all lost for the year 1865.

by three ships. The catenaries concerned in these operations were illustrated by a chain with 15 per cent. of slack hauled up simultaneously at three points.

The plan which seemed to the speaker surest and simplest is to cut the cable at any chosen point, far enough eastward of the present broken end to be clear of entanglement of lost buoy-rope, grapnels, and the loose end of the electric cable itself; and then, or as soon as possible after, to grapple and lift at a point about three miles farther eastward. This could be well and safely done by two ships, one of them with a cutting grapnel, and the other (the Great Eastern herself) with a holding grapnel. The latter, on hooking, should haul up cautiously, never going beyond a safe strain, as shown by the dynamometer. The other, when assured that the Great Eastern has the cable, should haul up, at first cautiously, but ultimately, when the cable is got well off the bottom by the Great Eastern, the western ship should move slowly eastwards, and haul up with force enough to cut or break the cable. This leaves three miles of free cable on the western side of the Great Eastern's grapnel, which will yield freely eastwards (even if partly lying along the bottom at first), and allow the Great Eastern to haul up and work slowly eastwards, so as to keep its grappling rope, and therefore ultimately the portions of electric cable hanging down on the two sides of its grapnel, as nearly vertical as is necessary to make sure work of getting the cable on board. This plan was illustrated by lifting, by aid of two grapnels, a very fragile chain (a common brass chain in short lengths, joined by links of fine cotton thread) from the floor of the Royal Society. It was also pointed out that it can be executed by one ship alone, with only a little delay, but with scarcely any risk of failure. Thus, by first hooking the cable by a holding grapnel, and hauling it up 200 or 300 fathoms from the bottom, it may be left there hanging by the grapnel-rope on a buoy, while the ship proceeds three miles westwards, cuts the cable there, and returns to the buoy. Then, it is an easy matter, in any moderate weather, to haul up safely and get the cable on board.

The use of the dynamometer in dredging was explained; and the forces operating on the ship, the conditions of weather, and the means of keeping the ship in proper position during the process of slowly hauling in a cable, even if it were of strength quite insufficient to act, when nearly vertical, with any sensible force on the ship, were discussed at some length. The manageability of the Great Eastern, in skilful hands, had been proved to be very much better than could have been expected, and to be sufficient for the requirements in moderate weather. She has both screw and paddles—an advantage possessed by no other steamer in existence. By driving the screw at full power ahead, and backing the paddles, to prevent the ship from moving ahead, or (should the screw overpower the paddles), by driving the paddles full power astern, and driving at the same time the screw ahead with power enough to prevent the ship from going astern, "steerage way" is *created* by the lash of water from the screw against the rudder; and thus the Great Eastern may be effectually steered without going ahead. Thus she is, in calm or moderate weather, almost as manageable as a small tug steamer, with reversing paddles, or as a rowing boat. She can be made still more manageable than she proved to be in 1865, by arranging to disconnect either paddle at any moment; which, the speaker was informed by Mr Canning, may easily be done.

The speaker referred to a letter he had received from Mr Canning, chief engineer of the Telegraph Construction and Maintenance Company, informing him that it is intended to use three ships, and to be provided both with cutting and with holding grapnels, and expressing great confidence as to the success of the attempt. In this confidence the speaker believed every practical man who witnessed the Atlantic operations of 1865 shared, as did also, to his knowledge, other engineers who were not present on that expedition, but who were well acquainted with the practice of cable-laying and mending in various seas, especially in the Mediterranean. The more he thought of it himself, both from what he had witnessed on board the Great Eastern, and from attempts to estimate on dynamical principles the forces concerned, the more confident he felt that the contractors would succeed next summer in utilising the cable partly laid in 1865, and completing it into an electrically perfect telegraphic line between Valencia and Newfoundland.

APPENDIX I.

Descriptions of the Atlantic Cables of 1858 *and* 1865.

(Distance from Ireland to Newfoundland, 1670 Nautical Miles.)

Old Atlantic Cable, 1858.

Conductor.—A copper strand, consisting of seven wires (six laid round one), and weighing 107 lbs. per nautical mile.

Insulator.—Gutta percha laid on in three coverings, and weighing 261 lbs. per knot.

External Protection.—Eighteen strands of charcoal iron wire, each strand composed of seven wires (six laid round one), laid spirally round the core, which latter was previously padded with a serving of hemp saturated with a tar mixture. The separate wires were each 22 gauge; the stand complete was No. 14 gauge.

Circumference of Finished Cable, 2 inches.

Weight in Air, 20 cwt. per nautical mile.

Weight in Water, 13·4 cwt. per nautical mile.

Breaking Strain, 3 tons 5 cwt., or equal to 4·85 times the cable's weight in water per mile. Hence the cable would bear its own weight in nearly five miles depth of water, or 2·05 times the—

Deepest Water to be encountered, 2400 fathoms, being less than 2½ nautical miles.

Length of Cable Shipped, 2174 nautical miles.

New Atlantic Cable, 1865.

Conductor.—Copper strand consisting of seven wires (six laid round one), and weighing 300 lbs. per nautical mile, embedded for solidity in Chatterton's compound. Diameter of single wire ·048 = ordinary 18 gauge. Gauge of strand ·144 = ordinary No. 10 gauge.

Insulation.—Gutta percha, four layers of which are laid on alternately with four thin layers of Chatterton's compound. The weight of the entire insulation 400 lbs. per nautical mile. Diameter of core ·464 of an inch; circumference of core 1·46 inches.

External Protection.—Ten solid wires of diameter ·095 (No. 13 gauge) drawn from Webster and Horsfall's homogeneous iron, each wire surrounded separately with five strands of Manilla yarn, saturated with a preservative compound, and the whole laid spirally round the core, which latter is padded with ordinary hemp, saturated with preservative mixture.

Circumference of Finished Cable, 3·534 inches.

Weight in Air, 35 cwt. 3 qrs. per nautical mile.

Weight in Water, 14 cwt. per nautical mile.

Breaking Strain, 7 tons 15 cwt., or equal to eleven times the cable's weight in water per mile. Hence the cable will bear its own weight in eleven miles depth of water, or 4·64 times the—

Deepest Water to be encountered, 2400 fathoms, or less than $2\frac{1}{2}$ nautical miles.

Length of Cable Shipped, 2300 nautical miles.

II.

Let W be the weight of the cable per unit of its length in water; T the force with which the cable is held back at the point where it reaches the water (which may be practically regarded as equal to the force with which its egress from the ship is resisted by the paying-out machinery, the difference amounting only to the weight in air of a piece of cable equal in length to the height of the stern pulley above the water); P and Q the transverse and longitudinal components of the force of frictional resistance experienced by the cable in passing through the water from surface to bottom; i the inclination of its line to the horizon; D the depth of the water.

The whole length of cable from surface to bottom will be $\frac{D}{\sin i}$; and the transverse and longitudinal components of the weight of this portion are therefore $\frac{WD}{\sin i}\cos i$, and WD respectively. These are balanced by $P\frac{D}{\sin i}$ and $T + Q\frac{D}{\sin i}$.

Hence

$$P = W \cos i, \quad Q = \left(W - \frac{T}{D}\right) \sin i \quad . \quad . \quad . \quad . \quad . \quad . \quad (1.)$$

To find the corresponding components of the velocity of the cable through the water, which we shall denote by p and q, we have only to remark that the actual velocity of any portion of the cable in the water may be regarded as the resultant of two velocities,—one equal and parallel to that of the ship forwards, and the other obliquely downwards along the line of the cable, equal to that of the paying out, obliquely downwards along the line of the cable (since if the cable were not paid out, but simply dragged, while by any means kept in a straight line at any constant inclination, its motion would be simply that of the ship). Hence, if v be the ship's velocity, and u the velocity at which the cable is paid out from the ship, we have

$$p = v \sin i, \; q = u - v \cos i \quad . \; . \; . \; . \quad (2.)$$

Now, as probably an approximate, and therefore practically useful, hypothesis, we may suppose each component of fluid friction to depend solely on the corresponding component of the fluid velocity, and to be proportional to its square. Thus we may take

$$P = W \frac{p^2}{\mathfrak{p}^2}, \qquad Q = W \frac{q^2}{\mathfrak{q}^2} \quad . \; . \; . \; . \; . \; . \quad (3.)$$

where $\mathfrak{p}$ and $\mathfrak{q}$ denote the velocities, transverse and longitudinal, which would give frictions amounting to the weight of the cable; or, as we may call them, the transverse and longitudinal *settling velocities*. We may use these equations merely as introducing a convenient piece of notation for the components of fluid friction, without assuming any hypothesis, if we regard $\mathfrak{p}$ and $\mathfrak{q}$ as each some unknown function of p and q. It is probable that $\mathfrak{p}$ depends to some degree on q, although chiefly on p; and *vice versa*, $\mathfrak{q}$ to some degree on p, but chiefly on q. It is almost certain, however, from experiments such as those described in "Beaufoy's Nautical Experiments," that $\mathfrak{p}$ and $\mathfrak{q}$ are each *very nearly* constant for all practical velocities.

Eliminating p and q between (1), (2), and (3), we have

$$W \cos i = W \left(\frac{v \sin i}{\mathfrak{p}} \right)^2,$$

which gives

$$\mathfrak{p} = \frac{v \sin i}{\sqrt{\cos i}} \quad . \; . \; . \; . \quad (4.)$$

and

$$(WD - T) \sin i = WD \left(\frac{u - v \cos i}{\mathfrak{q}} \right)^2 \quad . \; . \; . \; . \quad (5.)$$

which gives

$$\mathfrak{q} = (u - v \cos i) \sqrt{\frac{WD}{(WD - T) \sin i}} \quad . \; . \; . \; . \quad (6.)$$

These formulæ apply to every case of uniform towing of a rope under water, or hauling in, or paying out, whether the lower end reaches the bottom or not, provided always the lower end is free from tension; but if it is not on the bottom, D must must denote its vertical depth at any moment, instead of the whole depth of the sea. To apply to the case of merely towing, we must put $u = 0$; or, to apply to hauling in, we must suppose u negative.

It is to be remarked that the inclination assumed by the cable under water does not depend on its longitudinal slip through the water (since we assume this not to influence the transverse component of fluid friction), and that, according to equation (4), it is simply determined by the ratio of the ship's speed to the transverse "settling velocity" of the cable.

The following table shows the ratio of the ship's speed to the "transverse settling velocity" of the cable for various degrees of inclination of the cable to the horizon :—

Inclination of Cable to Horizon.	Ratio of Ship's Speed to "*transverse settling velocity*" of Cable.
i	$\frac{v}{\mathfrak{p}}=\frac{\sqrt{\cos i}}{\sin i}$
5°	11·4518
angle whose sine is $\frac{1}{8\frac{1}{2}}$ 6° 45′	8·4784
10	5·7149
15	3·7973
20	2·8343
25	2·2013
30	1·8612
35	1·5779
40	1·3616
45°	1·1892
50	1·0466
51° 50′	1·0000
55	·9232
60	·8165
65	·7173
70	·6224
75	·5267
80	·4231
85	·0875

If the inclination of the cable had been exactly 6° 45′ when the speed of the Great Eastern was exactly $6\frac{1}{2}$ miles per hour, the value of $\mathfrak{p}$ for the Atlantic cable of 1865 would be exactly $6\frac{1}{2} \div 8{\cdot}478$, or ·765 of a mile per hour.

Appendix B

PROPAGATION OF THE ELECTRICAL IMPULSE IN A CYLINDRICAL CONDUCTOR

Propagation of the Electric Impulse in a Cylindrical Conductor of Limited Length During the Variable Period

The following derivation is from Bright, C. (1898). *Submarine Telegraphs: Their History, Construction and Working.* London. pp. 528–531. Only very minor changes in notation have been made.

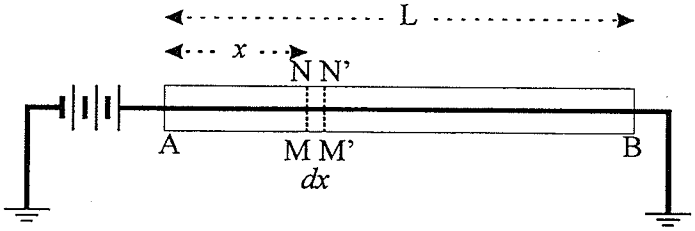

Figure 1:

Let AB (Figure 1) represent a cable with its end B to earth, connected up at A to a battery whose opposite pole is also to earth. In this cable we will consider a given volume of length dx included between two sections at right angles to the axis MN and $M'N'$, and situated at distances $AM = x$ and $AM' = x + dx$ from the point A. Expressing by

V_a the potential at A,

V the potential at M at the time t,

I_a the intensity, or strength, of the current at A at the same instant of time,

I the intensity, or strength, of the current at M at the same instant of time,

I_1 the intensity, or strength, of the current at B at the same instant of time,

ρ the conductor resistance per unit of length,

k the electro-static capacity of the core per unit of length,

r the resistance of the dielectric per unit of length,

L the length AB of the line,

the potential and intensity, or strength, of current at the time t in the section M′ N′ will be $V + dV$ and $I + dI$.

The quantity of electricity Idt which spreads itself over the section MN in the time dt will divide into three parts; the first, which will proceed along the conductor and spread over the section $M'N'$, is represented by $(I + dI)dt$; the second part, which traverses the insulation of the included portion $MN\ M'N'$, whose resistance is $\frac{r}{dx}$, will be equal to

$$\frac{V}{\frac{r}{dx}}dt$$

the third part will increase the electro-static charge in the included portion of cable, and can be expressed by

$$kd\frac{dV}{dt}dt$$

We now have

$$Idt = (I + dI)dt + V\frac{dx}{r}dt + k\frac{dV}{dt}dxdt$$

Reducing and remarking that by Ohm's law

$$I = \frac{dV}{\rho dx} \tag{1}$$

whence

$$dI = -\frac{1}{\rho}\frac{d^2V}{dx^2}dx$$

we get

$$\frac{1}{\rho}\frac{d^2V}{dx^2} - k\frac{dV}{dt} - \frac{1}{r}V = 0$$

or, assuming that

$$k\rho = a^2 \tag{2}$$

and

$$\frac{\rho}{r} = \beta^2 \tag{3}$$

$$\frac{d^2V}{dx^2} - a^2\frac{dV}{dt} - \beta^2 V = 0 \tag{4}$$

The general integration of this equation has been given by Fourier, and is expressed thus–

$$\frac{V}{V_0} = \frac{e^{\beta(L-x)} - e^{-\beta(L-x)}}{e^{\beta L} - e^{-\beta L}} - 2\pi e^{-\frac{t}{kr}} \sum_{n=1}^{n=\infty} \frac{n}{n^2\pi^2 + \beta^2 L^2} e^{-\frac{n^2\pi^2}{a^2L^2}t} \sin\frac{n\pi}{L}x$$

As a rule ρ does not exceed 10 or 12 ohms, and r reaches from 8,000 to 10,000 megohms; β^2 being therefore less than $\frac{1}{10^9}$. If we take $\beta^2 = 0$, which is the same thing as making $r = \infty$, or entirely neglecting loss of electricity through the insulation, the above integration is simplified and becomes

$$\frac{V}{V_0} = \frac{L-x}{L} - 2\sum_{n=1}^{n=\infty} \frac{1}{n\pi} e^{-\frac{n^2\pi^2}{a^2L^2}t} \sin\frac{n\pi}{L}x \tag{5}$$

Differentiating as regards x, and carrying the value obtained for $\frac{dV}{dx}$ into equation (1), we get for the current strength at the distance x

$$I = \frac{V_a}{\rho L}(1 + 2\sum_{n=1}^{n=\infty} e^{-\frac{n^2\pi^2}{a^2L^2}t} \cos\frac{n\pi}{L}x)$$

At the end B of the conductor which is then to earth, $x = 1$; $\sin n\pi$ being always *nil*, the potential is *nil*, and the current I_1 is

$$I_1 = \frac{V_0}{\rho L}(1 + 2\sum_{n=1}^{n=\infty} e^{-\frac{n^2\pi^2}{a^2L^2}t} \cos n\pi) \tag{6}$$

By giving to n consecutive values 1, 2, 3 ... the cosine acquires alternate values equal to -1 and +1. So that if we assume, for abbreviation, that

$$e^{-\frac{\pi^2}{a^2L^2}t} = u \tag{7}$$

equation (6) becomes

$$I_1 = \frac{V_0}{\rho L}[1 - 2(u - u^4 + u^9 - u^{16} + u^{25} - ...)] = F(t) \tag{8}$$

With extremely small values of t, u tends towards unity; at the limit the series $u - u^4 + u^9 ...$ equals $\frac{1}{2}$, and the current intensity is nothing. As the time interval increases, so u diminishes, the series decreasing and the current increasing; but according to Sir William Thomson, the series only differs sensibly from its minimum value $\frac{1}{2}$ when

$$u > \frac{3}{4}$$

Using τ to express the time when this condition is attained, we have

$$e^{-\frac{\pi^2 \tau}{a^2 L^2}} = \frac{3}{4} \tag{9}$$

whence

$$\tau = \frac{a^2 L^2}{\pi^2} \ln \frac{4}{3} \tag{10}$$

being expressed in seconds if a and L are expressed in C.G.S. units,* or

$$\tau = \frac{k \rho L^2}{10^6} \times 0.02915 \text{ second} \tag{11}$$

where k stands for the electro-static capacity of the cable in microfarads per naut, ρ the conductor resistance per naut in ohms, and L its length in nauts,

$$\tau = \frac{RC}{10^6} \times 0.02915 \text{ second} \tag{12}$$

R representing the total conductor resistance in ohms, and K the total capacity of the line in microfarads.

From this point onwards the series tends towards 0, and I_1 increases up to its limit of value $\frac{V_0}{\rho L}$, which is only reached after an infinitely great interval of time.

Appendix C

SPECIFICATIONS FOR THE ATLANTIC CABLES

Specifications for the Atlantic Cables

Year	Length	Breaking Strength	Linear Density in Air	Diameter
1858	3795 km	$2.89\text{x}10^4$ N	564 kg/km	1.62 cm
1866	3428 km	$6.89\text{x}10^4$ N	1008 kg/km	2.86 cm

Table: Atlantic Cable Characteristics

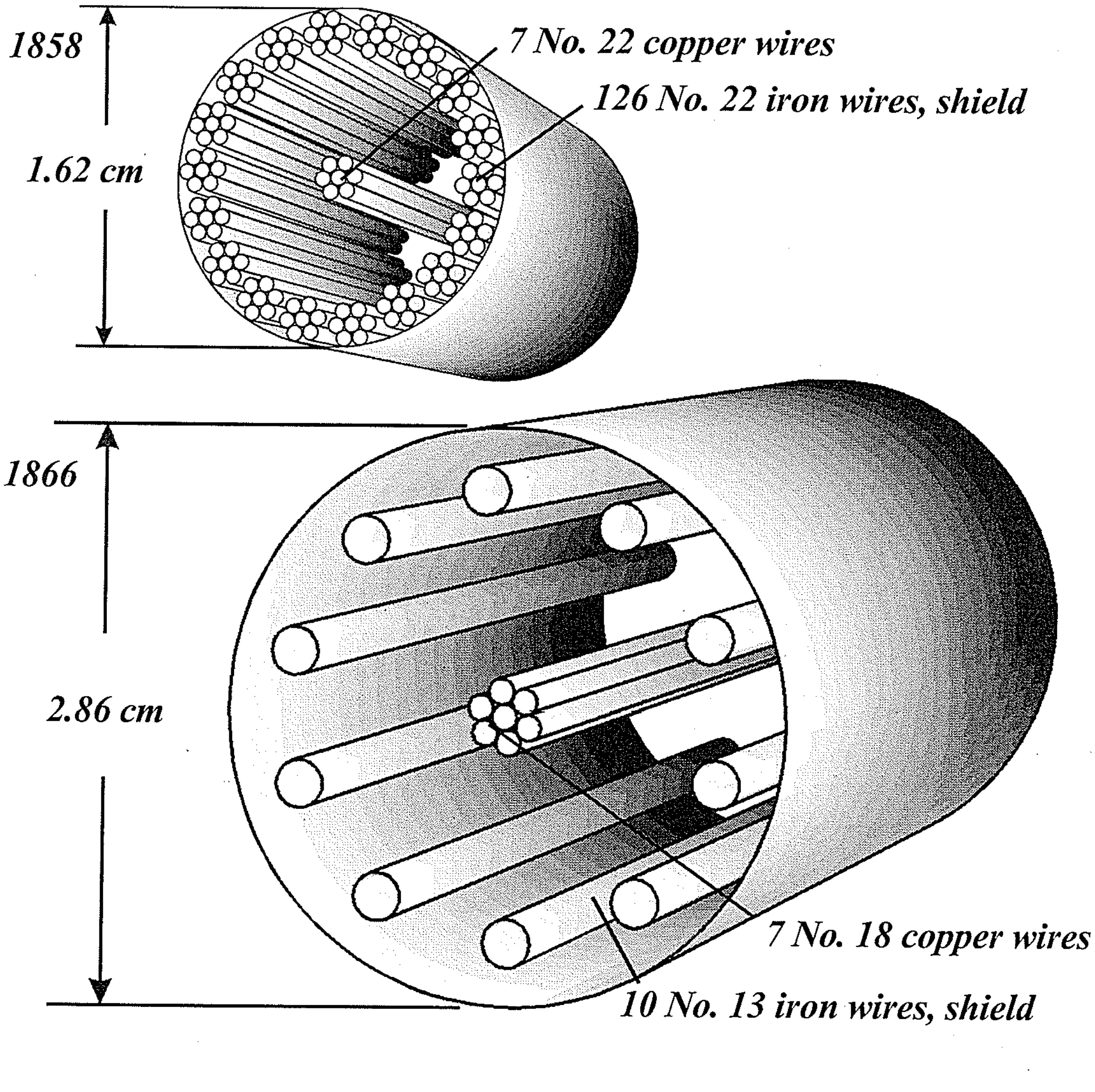

Figure: The Atlantic Cables, Insulation Not Shown

Appendix D

QUICK KELVIN FACTS

Quick Kelvin Facts

Sir William Thomson, Baron Kelvin of Largs

- Entered university at age 10
- Published first paper at age 16 in which he defended the mathematical theory of Fourier.
- Published about 600 papers in his lifetime
- Originated the Kelvin or absolute temperature scale
- Formulated the familiar version of the second law of thermodynamics:

> *It is impossible to devise an engine which, working in a cycle, shall produce no effect other than the extraction of heat from a reservoir and the performance of an equal amount of mechanical work.*

- Gained personal fortune through patents and consulting surrounding the Atlantic Cable.
- Famous quotation:

> *If you can measure that of which you speak and express it in numbers, you know something about your subject; but if you cannot measure it, your knowledge is of a very meagre and unsatisfactory kind.*

Appendix E

EVALUATION OF GROUP PRESENTATION

Atlantic Cable Problem – Evaluation of Completion Seminar

Name: ____________________

Date: ____________________

	Possible	Actual
Organization		
Introduction	1	
Logical development	1	
Transitions	1	
Ending	1	
Oral Delivery*		
Clarity, audibility	4	
Visual Material		
Legible, attractive, professionally presented	4	
Content		
Definition of context: physics problems, history of science	1	
Description of investigations	1	
Presentation of results	1	
Conclusion	1	
Answers to Questions*		
Demonstration of knowledge	4	
Total	20	

* Individual evaluation

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