A CURRICULUM DESIGN FRAMEWORK FOR SCIENCE EDUCATION BASED ON THE HISTORY OF SCIENCE

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ABSTRACT

Over many decades, much has been written about the use of the history of science in science education, particularly at the secondary school level. Course descriptions published by various education authorities have often included reference to the history of science, although student texts and formal assessment tools have not adequately developed or emphasised that area of study in a way which reflects its significance and potential value. These factors, combined with many teachers’ lack of background in the area, have meant that what happens in many classrooms does not reflect the loftier sentiments expressed in the guiding principles of the course outlines.

“Scientific Literacy” has been used as a general theme for science education during the second half of the twentieth century, and particularly since the early 1980s. There has been much debate about the meaning of the concept but some common features have emerged. Among these are the need for students to gain an understanding of the nature of science and to have some appreciation of the history of science. This thesis is based on an acceptance of the Scientific Literacy imperative and on its connection to the development of students as socially responsible members of society. In doing so, the case is made for the history of science to be an essential precursor to an understanding of the nature of science and ultimately, therefore, to the attainment of Scientific Literacy. It is not suggested that a history of science course per se should be taught at secondary school level - the history should be used as a vehicle to address and develop the concepts and themes of existing courses.

A new approach to curriculum development requires a framework on which it is based. The central aim of this thesis is the production of such a design framework which is entitled the ‘Dimensions of Science’. It is based on a curriculum theory which views education as the transmission of culture and, in particular, the culture of science and its relationship with the wider society. In doing so, it draws on important features of the nature of science.

To illustrate how the framework could be applied to a common topic in senior secondary school courses, the history of development of ideas in optics is examined. The ‘Dimensions of Science’ are used as the basis of analysis to show how it is possible to encounter examples of each Dimension in a study of a particular area of science while still attending to the conceptual ideas deemed important in existing course outlines.
STATEMENT of AUTHORSHIP

This is to certify that

(i) the thesis comprises only my original work towards the PhD

(ii) due acknowledgement has been made in the text to all other material used

(iii) the thesis is less than 100,000 words in length.

Paul McCOLL
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CHAPTER 1

INTRODUCTION

1.1 Rationale for the Research

Curriculum statements and course outlines in Science Education for secondary schools in Australia and other countries have followed a similar plan for decades. In essence, science courses have tended to reflect the academic content of undergraduate studies, but taught at a level and complexity which is appropriate to the age of secondary school students. Both (1977) observed as much when he commented that

[N]o one now looks upon the senior years as solely a preparation for university study – but my contention is that our syllabuses make it appear that this is still our chief aim. (p. 44)

Both’s analysis was confirmed later by Fensham (1985) who described the characteristics of the school science curriculum at the time:

[I]t has its content determined for it largely by selecting out those simple but abstract concepts and principles that are the logical starting points for the learning of the abstract knowledge that is such a dominant component of specialist courses of study in the sciences at university or college level. (p. 419)

These comments, made in Fensham’s widely cited work entitled Science For All: A Reflective Essay and written in the context of a wider view than just the Australian perspective, suggest that the narrowly-focused academic theme of secondary curricula was common in many countries.

More recently still, as a result of a widely researched investigation on science education in Australia, Goodrum, Hackling and Rennie (2001) concluded that

[a]t the secondary level, in particular, science is traditional, discipline-based and dominated by content. (p. 152)

Since the late 1980s, the American Association for the Advancement of Science (1989) has been developing a genuinely new direction for science at secondary school and has published general principles and detailed outlines of their approach under the umbrella title of Project 2061.

In Australia, since about the same time, there have been national frameworks for science education which have been adopted to varying degrees in each of the
States. However Cross (1997), in a paper entitled “The Sixties come to School”, pointed out the trend reversal which some of these State interpretations represent at the junior secondary level.

In Victoria, during the 1990s, the junior science framework was divided into Curriculum Strands which include Natural and Processed Materials, Energy and Change, and Life and Living. They were generally interpreted by teachers as euphemisms for Chemistry, Physics and Biology, and Goodrum, Hackling and Rennie (2001) observed that “these documents are grounded in the traditional disciplines” (p. 486). Consequently the framework and its attendant Strands still resulted in a traditional curriculum implementation and pedagogy, despite any intended change in emphasis underlying the newly developed frameworks. Goodrum, Hackling and Rennie found that teaching was largely tailored to the demands of higher levels within secondary science education. Course outlines at this level, in turn, were influenced by tertiary demands, as was found by Hart (2001). It appears that things have changed little since Both (1977) referred to the “considerable influence” which university scientists have on curriculum committees, and, more recently, Fensham (1993) reported his direct experiences and research elsewhere concerning “academic influence”. There has been much debate worldwide by educational researchers, science teachers and others interested in science education regarding the suitability of such curricula and the teaching approaches and underlying values they imply.

Despite the universality of such narrowly-focused programs, there are other approaches which have been proposed at various times throughout the twentieth century. Aside from such curriculum programs, there has been much discussion throughout that time regarding the goals of science education and these imply a wider curriculum focus than that described above. Specifically, the call for science literacy requires a fundamental reappraisal of traditional curriculum development and classroom teaching approaches. Goodrum, Hackling and Rennie (2001) noted the underlying scientific literacy approach of the national frameworks in Australia, but they also recognised the lack of synergy between the described and actual science education programs.

Significant within debates regarding new approaches to science education have been the importance of an appreciation of the nature of science and the adoption
of a socially responsible approach to teaching and learning. Each of these approaches has been linked to the need for an awareness of the history of science. The central argument of this thesis is that a science curriculum design based on historical studies is essential to the attainment of scientific literacy which, in any of its recent descriptions, has an understanding of the nature of science as a key theme. A historical approach highlights and illustrates the many facets of the nature of science, in addition to providing a vehicle for the teaching of other aspects of science including the scientific content which is central to so many traditional science courses. There is no requirement for a specific historical era to be chosen. It is possible to see key elements in the processes of scientific development whenever and wherever it is carried out.

This thesis arose from a personal recognition, based on over 20 years of science teaching at the secondary level in Victoria, that learning science, and learning about science, could be made far more interesting for students if the histories of people and events involved were made the focus of study - if science was seen as a product of human endeavour. An increase in interest provides greater motivation which then provides a basis for greater student learning. Such an approach would require a re-examination of science curriculum design and its implementation. Student enrolments in the post-compulsory years of secondary education have been at low levels for some time. This has been widely documented (see, for instance, Goodrum et al.) and is of concern to everyone associated with science education. Different curriculum approaches are required not only to reverse the enrolment decline but also to address the changing demographic of the student cohort throughout secondary school. For some time, student retention rates through secondary education have been high, and only a small number of students progress to tertiary studies in science. Accordingly, the need to provide a background to tertiary studies is no longer as imperative as it may have been in past years. This is reflected in the various statements and goals associated with the scientific literacy imperative. If the history of science could provide the basis for curriculum development, then it should clearly emanate from a curriculum design framework. These trains of thought prompted and drove the research which eventually led to the thesis structure outlined in section 5 of this chapter.
1.2 Research Questions

The primary and central question which prompted this research was concerned with the history of science:

*Can the history of science be employed as an effective approach in the teaching of science at secondary school?*

The specific questions which grew from that include the following:

1) To what extent has there been on-going academic discussion which recognises the value of the history of science in secondary school science education and what are the implications of this discussion for curriculum development?

2) What does the current focus on science literacy imply for the design of a secondary school science education curriculum?

3) If there is a clear connection between scientific literacy, the nature of science and the history of science, how should a science curriculum be designed so as to firmly establish and demonstrate the links between these concepts?

4) Could the broad framework of such a curriculum design provide an effective basis on which to develop a teaching program in a specific area of science?

5) And finally, what changes would need to occur to enable such a curriculum design approach to be implemented?

It was not the intention to examine and answer this last question directly within this research. Rather its purpose is to consider the next steps which would be required, beyond this research, to enable such a curriculum framework and a historical approach to be adopted as a means to achieve scientific literacy. These are discussed in general terms in the concluding chapter.

1.3 Research Methodology

In addressing the central question it has been necessary to investigate and draw together ideas from a range of contexts. Principally, these have included research in the following directions: a history of developments in the science of Optics, philosophies and sociologies of science, the meanings of the nature of science, interpretations of the scientific literacy concept, and approaches to curriculum design.
There is an extensive and ever-expanding resource base regarding the history of science across all areas of the field. It could reasonably be said that any area of science which might be associated with secondary education would have much written about its history either in book or journal form. For a teacher who adopts an historical approach to science studies, an awareness of that history in relation to a specific topic is naturally one of the essential prerequisites. But it is not a sufficient background for the development of a teaching program. Consideration needs to be given as to how such knowledge should be interpreted. There is a common tendency for those who study history to do so through a lens shaped by current knowledge and values. Such an interpretation of history becomes judgmental and limits the real understanding of events as they occurred at the time in question. An understanding of why and how a particular set of events took place in the past, and why others may not have occurred, also requires an understanding of the surrounding social, technological and other influences. Even more fundamentally, a different era involves a different culture, a different way in which life was conducted. ‘Then’ is not the same as ‘now’ in a similar sense to that which Kuhn (1970) used to describe two paradigms as being ‘incommensurable’. What occurred in the past cannot be judged or explained in today’s terms. This requires that the past should be studied with a respect for the era which may be made easier by attempting to empathise with it, as far as that may be possible from today’s standpoint. History is not just a statement of names, dates and events.

Understanding the history of science requires more than an appropriately contextualized examination of the people and events pertaining to a particular era. The next step required to appreciate the significance of that history is to determine whether what has been studied forms part of a wider process which has recognizable characteristics. The leads to a study of some philosophies of science, not to arrive at a particular or agreed viewpoint, but to raise an awareness of some of the philosophies which have been proposed at various times. Research in this area expands to include a study of what has come to be called ‘the nature of science’. This inevitably results in an encounter with the somewhat controversial area of the sociology of science.

An awareness of history, even when interpreted empathetically and within a philosophical framework, is still not sufficient for what is required in addressing the central question of this thesis. If it were, then the proposal would simply be for a
history of science course, but such is not the case. History is involved as a vehicle for a wider purpose. A scientifically literate and socially responsible citizenry needs to understand what science is and is capable of, in addition to knowing what it says and does. The former notions imply an appreciation of the characteristics of science, while the latter refer to scientific knowledge. Even this much tends to simplify the situation. On the one hand, there are some things which ‘science’ (that is, the institution of science) says – these are the widely accepted explanations and theory structures which are fundamental to the various scientific disciplines. On the other hand, there are things which ‘scientists’ say – statements and explanations which have yet to gain widespread acceptance and which may be at variance with what other scientists say. Such a situation can only be accepted by the wider public without cynicism and disbelief if the processes and characteristics of science are properly understood. Events which have occurred throughout the history of science are required to demonstrate the various characteristics of science.

In order to ensure that these characteristics are not seen as an arbitrary set of descriptors, it is important that they are part of a broad framework of understanding the institution of science and its relationship with other social institutions. This can be achieved if one considers the existence of a culture of science within the culture of a wider society. Accordingly, a cultural analysis which is applied to society in general may be appropriately used, with modification, as a framework for the study and analysis of the culture of science.

The history of science and an understanding of the characteristics of science, on their own, do not produce a science education program. A science course must be based on a curriculum design which reflects the aims of science education. These aims are often spoken of in terms of the attainment of scientific literacy. An awareness of these goals and of a design framework, or proposals for alternative goals and designs, form the foundation of a science education program which can be developed through the implementation of an historical approach.

These latter processes represent the contribution which this thesis makes to the area of science curriculum development. The historical approach to science education which is described in this research is an integral part of a curriculum design framework for science which has been modified from a design framework which was proposed by Lawton (1989) for education generally.
Although much has been written by many contributors over many years in support of the use of history in science education, there has been little in the way of relating such an approach to a curriculum design framework. This thesis proposes a rationale for the use of history of science which is embedded in such a framework.

1.4 Scope and Limitations

The area of schooling which was initially envisaged for the application of an historical approach was in the final year of the Physics course which is taught in Victorian secondary schools. All subjects at that level have their course outlines specified by a Board of Studies which operates within the State’s Education Department. When this thesis was first planned, that particular course included a topic entitled *Light and Matter*, and the topic was to be covered within the context of *Landmark Developments*. Although the time available for that topic within the teaching year was extremely short and the topic outline was still strongly focused on conceptual content, it nevertheless provided an opportunity for a historical focus to be officially adopted as an approach to the teaching of a science course. Accordingly, this research examines how the history of Optics could be used as the theme for teaching such a topic at the senior secondary level.

Notwithstanding the focus on that specific area, the applicability of this thesis is intended to be much wider than that. The thrust of this research work is directed towards the proposal for a curriculum design framework rather than simply being an examination of a means to teach optics. Optics happens to have been chosen as the topic to illustrate the application of that framework. Accordingly, other areas of physics could equally well have been chosen; likewise, another subject could even have been chosen (biology or chemistry to mention the main two other senior subjects taught at secondary school). There is no reason in principle why the approach should not be employed at any level of science education, not just in the senior years, and the author encourages its adoption at other levels as a means of conveying a more accurate understanding of what ‘science’ means.

Part of this research includes an examination of aspects of the history of optics, but it is limited to that much of history as is required to illustrate aspects of the nature of science. It is not intended that it should be a comprehensive historical study in its own right. The purpose of the thesis is to guide science curriculum development
rather than to produce an academic historical analysis. Similarly, the research and discussion surrounding the philosophy and sociology of science in Chapter 4 is not undertaken with the intention of arriving at a comprehensive, summative or novel interpretation of those fields. If a curriculum design is to eventually result in students gaining an appreciation of the institution of science, and of its processes and products, then the way in which it is portrayed needs to be given due thought. As has often been pointed out (for example, by Nunan (1977) and McComas, Almazroa and Clough(1998)), a denial of the need to be aware of or to explicitly teach about the nature of science still results in students gaining an understanding of what science means. Inevitably, the view they develop under such circumstances does not accord with what many observers of science believe is appropriate. Teachers, as the implementers of the curriculum, need to be aware of the messages they convey in this regard and to realise that not to incorporate the nature of science in the curriculum is simply to provide students with another view of it. Sufficient of the nature of science is examined in this research so as to provide a basis for it to be an integral component of a science curriculum design, and a range of references is provided to enable a fuller study of the characteristics of science.

Regarding the curriculum aspects of the thesis, distinctions are recognised between design, development and implementation. The three concepts refer to stages in the production of a teaching program. The development stage grows from the design and draws together appropriate aspects of learning theories, classroom pedagogies and accessible resources to arrive at the plan which is then implemented over a period of time with a class. This thesis is limited to the first of these stages. What eventually occurs in the classroom as a result of adopting the approach described by this research will depend on circumstances which ultimately the teacher takes into account, factors such as the age of the students, the size and character of the class, resources available, and so on. These physical determinants are combined by the teacher with theories of how students learn effectively to produce the set of activities which becomes the classroom program. There have been many attempts, proposals and discussions regarding these development or implementation phases of course production specifically related to the use of history of science; some of these are referred to in the literature review which follows. Very few of these appear to
have been founded on a rational design framework. This thesis is intended to fill that gap.

1.5 Thesis Structure

The central question of this research concerns the use of history as a vehicle for the teaching of science. Accordingly, Chapter 2 covers a survey of the scientific and educational literature to establish the status of such an approach. The summary of that survey is undertaken from two angles, referred to as the ‘Contributors’ and the ‘Contributions’. The views of five contributors whose work has been of significance throughout the twentieth century are examined. There are, however, many others who have added impetus to the cause of history in science, either by arguing the case for its adoption or by describing specific courses which have been or could be constructed with that focus. A range of these contributions is scanned in the second half of Chapter 2.

As indicated in section 3 above, this thesis draws together ideas from a range of directions, not just the one directly related to history of science in science education. In order to arrive at a coherent plan for science education it has been necessary to examine the developing meanings of scientific literacy as a goal of science education and this is undertaken in Chapter 3.

Central to the range of descriptions of the scientific literacy goal is what is variously termed the ‘nature of science’ or the ‘characteristics of science’. Included among the detailed interpretations of these concepts are the philosophies of science, the views which describe science in sociological terms, and the various processes and products of the ‘scientific enterprise’.

The focus of Chapter 4 is on the characteristics of science. As has been mentioned in the previous section, this chapter is not intended to be a definitive summary of the nature of science and its various components but rather to highlight some of the important interpretations of science which have been proposed in recent decades.

In Chapter 5 the discussion establishes significant links between the scientific literacy goal and the characteristics of science, and, even more importantly, the essential connection between the characteristics of science and the history of science.
In effect, the argument concludes that scientific literacy cannot be achieved without the incorporation of the history of science into a science education program.

An educational program requires a framework on which it is built if it is to be widely understood and adopted, and if it is to have validity beyond the isolated contributions which characterise many of the literature suggestions highlighted in Chapter 2. Lawton has made significant contributions to the area of curriculum design, and draws on work by Tyler, Stenhouse and others in constructing a curriculum framework based on the concept of education as a process of transmission of culture. He suggests nine cultural ‘systems’ which are important characteristics of a society and which therefore would be worthy of transmission to future generations. In Chapter 6 his ‘systems’ approach is adopted for this thesis and modified to apply it specifically to the ‘science’ component of education. Parallels to Lawton’s nine systems are proposed and justified by reference to particular instances within the scientific enterprise.

The next two chapters demonstrate how the historical approach can be used as the focus for science education by selecting a particular field of science (Optics) and using it to demonstrate the application of the modification of Lawton’s design framework proposed in Chapter 6. Chapter 7 examines events in the history of optics, principally during the seventeenth century, but also covering other periods of time. The era chosen for classroom implementation will depend to some extent on the optical concepts (the scientific knowledge) which are to be addressed as an important component of the final curriculum program. The seventeenth century is an appropriate era for the study of developments in understanding the nature of light, and the properties of refraction, colour and diffraction; the early nineteenth century provides an opportunity for examining the role of interference as a phenomenon and also the debate concerning an appropriate model for light; the late nineteenth and early twentieth centuries is a time for using the photoelectric effect as the focus for further debate on the nature of light. Any of these eras provide opportunities to examine the characteristics of science.

In Chapter 8, the curriculum design framework of Chapter 6 is overlaid on the historical examination of Chapter 7 to illustrate how the framework can be applied in practice. Although the discussion focuses on optics, the examples chosen are of
sufficient scope to suggest that the framework could be applied with equal success to other areas of science, or to other eras including the recent past.

Chapter 9 concludes with an overview and evaluation of the thesis proposal, and a consideration of what further steps would need to occur if that proposal were to be successfully implemented.

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CHAPTER
2

CONTRIBUTORS AND CONTRIBUTIONS

2.1 Introduction

The use of history, including the human and social issues which it encompasses, as a framework within which physics might be taught has been advocated at various times over the past hundred years, and more continuously so in recent decades. This chapter examines the developments associated with the calls for an historical approach to science education over much of that period of time. The analysis is undertaken from two perspectives: the general issues and arguments raised in the debate, and the names and views of five of the most significant contributors. There have been many forums within which the arguments have been aired: academic conferences, journal articles and books. Summaries of some of the earlier discussions have been given by Sherratt (1982 and 1983) and Jenkins (1990).

In the first half of the chapter, the literature relating to the main aspects of the discussion will be examined. These centre on the aims of science education, the benefits which ensue from adopting an historical approach, and the relationship between the approach and current theories of learning.

The second half of this chapter considers the significant contributors. Among the diverse views expressed in this debate over some extended period of time there have been some people who have been much more influential than others. This influence can be gauged by the number of articles written, number of citations made by other writers, length of time in the field, specific judgmental comments made by other writers and involvement at the administration level in terms of such activities as conferences organised or books edited.

It is not the purpose of this thesis to undertake a quantitative analysis of the field. There are many people who could be listed as being leaders in the debate. In this thesis, five such contributors are considered. They are Ernst Mach, James Conant, Gerald Holton, Stephen Brush and Michael Matthews. Their views will be discussed in section 2.3 and their main outlooks presented, along with some views which others have expressed about
these writers’ ideas. The first two were principally implementers of a historical approach, although Conant was a more traditional historian of science. It is reasonable to expect that Harvard University personnel would be likely to figure prominently among those who are leaders in the field because of the strength and pre-eminence of that institution’s History of Science department over more than fifty years. Conant is a central figure in the development of ideas, and in the widespread influence which the Harvard Department of History of Science had. Holton, another Harvard-based worker, taught physics at the tertiary level as a historical study both to convey the nature of science and to teach physics. For almost thirty years, Brush has been enthusiastically contributing to all aspects of the development of a history of physics approach; and, most recently, Matthews has written widely in journals in addition to editing special issues, establishing a new journal (*Science & Education*) devoted to the field, publishing books and organizing conferences and interest groups.

### 2.1.1 Terminology

In examining the literature, it is apparent that many articles which seem to be debating the same issues may actually be discussing different types of courses. There needs to be a distinction made between courses on ‘History of Physics’ and those on ‘History of Physics as a means of teaching Physics’; that is, for some courses, history of physics is the means to an end, while, for others, it is the end itself. There are some common features in the aims of each type of course, in their methodologies and in the understanding which students in each type of course have by the time their study is complete. Consequently, there is also some overlap in the application of literature articles to each study area.

There also appears to be some ambiguity in the direction of some articles resulting from the writer’s tendency to use the term ‘history of science’ in reference to both areas of study. ‘History of science’ is qualitatively as well as quantitatively different from a study of the ‘history of physics’. The former is more related to an overall structure of knowledge. Sarton (1950) described it as ‘more than a juxtaposition of all the histories of the special sciences, for its main purpose is to explain the interrelation of all the sciences,
their cooperative efforts, and their common aims and methods’. The history of physics, while still providing an opportunity to illustrate something of the nature of scientific enterprise, is more directly related to case studies.

At the secondary school level, the studies of ‘science’ and ‘physics’ refer to different subjects: one is usually taken between years 7 to 10 (the junior secondary school years) while the other is only taken at years 11 and 12. This gives rise to some ambiguity in literature articles, even within a single article in which the writer will use both terms, perhaps without meaning to refer to different studies.

Some writers specifically suggest that physics is the discipline which most satisfactorily illustrates the epistemology of science, others will use the term ‘science’ but will only use historical examples which are physics-centred, and others again will consciously use the term ‘science’ to indicate the broad discipline. In any case, the arguments put forward can be applied equally to each of the sub-disciplines within the whole scientific field. This thesis, however, relates primarily to physics at the secondary school level via a study of the history of optics and its use as the basis of the curriculum development exemplar in Chapter 8.

2.1.2 Literature Approaches

Relevant literature material can be divided into two main categories:

- Contributions related to the principles of the debate on the worth, style, methods and importance of socio-historical approaches
- Discussions of actual socio-historical developments, discoveries and theories which may act as useful material for educators or students.

Comparatively few contributions offer suggestions as to teaching methodology or curriculum design and development in this area, although this has begun to change very recently. This scarcity is particularly significant, given that the pedagogical skills required for the approach are not necessarily the same as those with which many science teachers are familiar with or well-practiced in and as is described in Goodrum, Hackling and
Rennie (2001); that is, the more formal, teacher-centred style of lecture, discussion and experiment (which itself tends to reinforce the notion of scientific positivism).

Contributions to the fundamentals of the debate (the first of the above two categories) have come from those who could primarily be considered ‘educators’ rather than ‘scientists’, ‘historians’, ‘philosophers’ or ‘sociologists’. These latter groups tend to provide input to discussions surrounding the second of the above two categories. This is understandable up to a point because the debate which centres around the teaching of physics content at secondary schools is of direct relevance to teachers (or teacher educators) and only indirectly related to the work of the others. This is not to say that there is no need for any contribution from the historians. Many have lamented the fact that there has been so little contact, for various reasons, between the various interest groups and, during recent years, this trend is being reversed.

Sometimes articles in the second category are quite clearly and deliberately written to indicate the educational possibilities of a particular event in scientific history, while other contributions are not specifically intended for education in the classroom sense, but are relevant nevertheless. These contributions may be of value to teachers, as part of their general background in the history, nature or scope of science. Alternatively, they may consist of ideas which can more explicitly be included in course design and ultimately in the classroom.

The educational philosophies of contributors writing the first type of article are clearly seen in the arguments they put forward espousing the historical approach. The aims of writers of the second type of article, however, are less obvious. Usually, their view of the purpose of an historical approach to science education can be inferred from the style of the course material they describe or the journal article they write. This latter group of people are not necessarily involved in the debate as to whether, and why, there should be some form of socio-historical approach - they have already accepted it, and have designed a course (usually for the tertiary educational level) which demonstrates their own particular idea of how such an approach might unfold.
2.2 The Significant Contributions

2.2.1 Principal Directions

Articles written about the socio-historical approach are intended to serve a variety of purposes. The main emphases include its relevance to the aims of science education, its compliance with the principles of currently-held theories of learning, the benefits which can arise through an adoption of the approach, classroom methodologies, and issues relating to implementation of such a course in schools. Other articles provide a description of the attempts which have actually been made to include history in science curricula. Until recently, there have been very few links made between these ideas and the concepts associated with scientific literacy or with the fundamentals of curriculum design. A broad perspective of these issues, especially regarding those ideas which have been expressed over the last couple of decades, can be gained from the outline which follows.

2.2.2 Aims

Uzzell (1978) described the changing emphases in aims for science education from the middle of the nineteenth century up until 1970. These were derived, in the main, from statements made during those years by governmental departments of education or by teacher associations. Given the long time-span of this study, it necessarily comments only briefly on the main thrust of each of the various science education statements made by government and teacher bodies during those years. Notwithstanding this, Uzzell made very little reference to any formal emphasis given to recommending courses containing any historical content. Sherratt (1982), however, saw a ‘landmark for history of science in school education’ (p.225) in the publication of the British Association’s Report of 1917 in that it gave prominence to history of science in the school curriculum. Sherratt quoted from that report:

> It is desirable .. to introduce into the teaching some account of the main achievements of science and of the methods by which they have been obtained .. There should be more of the spirit, and less of the valley of dry bones .. One way of doing this is by lessons on the history of science. (p.225)

Despite this conviction by the Association, in part II of his two papers, Sherratt (1983) pointed out that
on the evidence of the pages of S.S.R. [School Science Review], history of science in the school curriculum never became a burning issue during the inter-war period. (p.421).

Jenkin (1990) made similar observations not only for the early half of the century but even in the years up to the seventies, at least as regards British science curricula.

More recent opinions as to the purposes of science education, and in particular as to how the socio-historical approach is supportive of those aims, have been offered by various journal contributors.

Gauld (1977) described the aims of science education in terms of what the science teacher can reasonably be expected to achieve. He suggested that it is the responsibility of curriculum designers to determine a balance between developing scientific understanding, problem-solving skills, and a cultural appreciation of science. In addressing the third of these aims, Gauld recommended that

the various ways of interpreting historical data should all be included in a science course which chooses to illustrate the cultural context of science with historical material. (p.51)

Whitaker (1979) presumed that the main aims of physics education (at least in the minds of physics teachers) are to ensure that

the student should gain an understanding of the physical principles and techniques, and their application … [and] … an appreciation of the significance of the scientific approach, the various revolutions in man’s understanding of nature, the way in which science is carried on today and its place in modern life (p.108).

While recognizing the existence of faulty attempts in many classrooms, he nevertheless suggested that the teaching of a reasonable amount of historical material is appropriate in order to achieve the second part of the above aim statement.

2.2.3 The Historical Approach and Learning Theory

The concept of parallelism and the principles of constructivism are the aspects of educational theory which are sometimes called upon in explaining or justifying a socio-historical approach.

Parallelism refers to the Piagetian connection between the historical development of science and the intellectual development of an individual. In discussing Piaget’s genetic epistemology, Flavell (1963) explained that Piaget
attempts to show parallels between historical and ontogenetic evolutions of (a) concept ...
The subject of his historicodevelopmental analysis may be broader than a single concept ... it may subtend a group of interrelated concepts or even a whole field of knowledge ... But whatever the content, the general strategy is to apply the constructs of his developmental theory ... to the historical process, the latter construed as an evolution across a number of adult minds at least partially analyzable in the same terms as the evolution within a single immature one. (p.252)

Flavell summarized this as ‘ontogenesis-recapitulates-history’. Sherratt (1982) traced the notion of parallelism back much further than Piaget:

During the previous century several authors had argued that the history of mankind was indicative of the several stages through which every child passed to maturity. This belief in parallelism ... naturally focussed attention on the history of science. During the succeeding decades the supposed parallel between individual and historical development was frequently used to justify the use of the historical method and the inclusion of historical material in school science courses. (p.228)

More recently, Wandersee (1992) discussed what he termed the ‘historicality of cognition’. He observed that

There is a growing consensus that the historical aspects of cognition are important for understanding both how individuals and disciplines know what they know. (p.425)

He believed in the importance of an appreciation of this viewpoint in addressing students’ alternative conceptions in science. He set himself apart from strict Piagetian parallelism, however, by stating that there is no research evidence which shows that students actually repeat the historical development of a scientific concept in their personal construction of such a concept. It was Wandersee’s opinion that children hold misconceptions which are often similar to those held at some time in the past during the historical development of a topic. To this extent, a knowledge of the history of science can assist the educator to anticipate student difficulties. His preferred use of the history of science in the classroom is to produce a short story relating some particular incident, especially a controversial or dramatic one, in the life of a scientist.

The connection between science history and students’ cognitive development formed the basis of a post graduate course for teachers in which Stavy (1992) is involved. She explained that, in that course,
Special emphasis is put on presenting conceptual changes ... in the history of science and in students thinking and on examining similarities and differences. (p.467)

Piaget’s claim of parallels in genetic epistemology between the individual and the scientific community over time are not universally agreed to, however. Siegel (1982), for example, discussed the issue and examines both the cases for and against the parallels. For example, he pointed to dual meanings of the term ‘objective’ when used by Piaget in connection with an individual’s movement away from egocentrism and science’s attempts to be unbiased. Other concerns he expressed relate to cumulative developmental change:

according to Piaget, cognitive development (at least major stage change) exhibits a uniform and total gain in cognitive power, while the development of science exhibits no such gain. On the contrary, science sometimes loses, in theory change, a significant amount of explanatory or ‘cognitive’ power. (p. 380)

Siegel’s concluding remarks granted some similarities:

for example, in both [areas of development] it may be the case that previously insoluble problems become soluble (p. 385)

but he denied that there was any ‘isomorphism’ between the two types of development or any examples of a universal mechanism of development illustrated by the two: ‘The parallel ... should be seen as partial, at best’ (p. 385).

Gauld (1991) also held a cautious view on the notion of parallelism in that he too recognized both the similarities and differences between individuals and science itself in the process of developing an understanding of a concept and in the conceptual frameworks which both groups construct. He expressed caveats on the adoption of too sweeping an acceptance of the Piagetian parallelism idea. Wherever there are similarities between individual and disciplinary development they are only superficial; the comparisons do not stand up to detailed examination. This is inevitably so for a number of reasons, not the least of which are, firstly, the difference in ages between children and past scientists and, secondly, the private and subconscious development which the student experiences compared with the public and conscious discussion of ideas which is characteristic of the scientific enterprise. Gauld pointed out that Piaget dealt more in generalities even when talking about the cognitive development of the individual and that this may not be
appropriate for teachers who have to deal with individuals and their differences. Nevertheless, he was still an advocate of the historical approach as a means of overcoming student misconceptions.

Knowledge about conceptual change in history thus becomes a source of strategies for changing student notions into ones closer to those of contemporary science. (p.137)

Gauld recommended that the first step in the classroom process must be to establish what the student’s (probably subconscious) current framework is by questioning and discussion. Then follows the adaptation of appropriate historical material, based on the results of this preliminary discussion. He concluded:

... similarities between the ideas of modern day school students and early scientists leads to the expectation that the history of science should be of value in helping students to change their concepts in appropriate ways. However, historical material, to be effective in the classroom, must also take into account the significant differences which exist between these ideas. (p.138)

Without specifically referring to constructivism, Gauld’s recommendations for the classroom approach were an elucidation of that theory of learning: the first step is to ascertain, and have the students clarify for themselves, what their current understanding and conceptual framework is. As Louden and Wallace (1990) explained:

... constructivists have proposed that school science should begin with children's own constructions of reality. Teachers should encourage students to make their own ideas explicit, present students with events which change their ideas, encourage the generation of alternative models and provide opportunities for students to use new ideas in a range of situations. (p.182)

Although constructivism (like any theory of learning) does not propose any one method of pedagogy to the exclusion of others, the combination of this theory and parallelism has suggested to some educators that there would be some benefit in the use of an historical approach to science education.

2.2.4 History of Physics and Scientific Literacy

The term ‘Scientific Literacy’ is explored in some detail in Chapter 3. In the context of this chapter, the frequent reference to historical approaches in publications which discuss scientific literacy is worthy of note.
Recent calls for an increased ability in this area frequently refer back to an issue of *Daedalus* in 1983 which was devoted to that concept and, more particularly, an article therein by Arons (1983) entitled ‘Achieving Wider Scientific Literacy’. In that article he described a range of characteristics (see chapter 3, section 3.3.3, for a complete listing of these) which a person might display if they are considered to be scientifically literate - many of these are directly related to a need to have some understanding of the history of science. Later, Arons (1988) summarized what might be meant by scientific literacy by suggesting that it is

some awareness of the nature of scientific thought, its modes of development and validation, its limitations, and its impact on human intellectual history and on society. (p.13).

He recognized that there were broader definitions which include acquisition of knowledge, but concentrated on his own statement for the purposes of that article.

In arguing for an increased scientific understanding, he echoed the views of Mach when he suggested, in Arons (1983), that

it is essential to back off, to slow up, cover less, and give students a chance to follow and absorb the development of a small number of major scientific ideas. (p.97).

He described some of the questions which he considered would be profitable for students to ponder over:

Why do we believe the earth revolves around the sun? ..... What do we mean by the concept ‘electric charge’? How does the concept originate? (p.98).

The examples which he discussed in some detail are selected to illustrate the ‘epistemological, philosophical, and historical aspects of science’ (p.107).

In taking up the science education catch-cry of the 1980s - ‘Science for All’ - Hodson and Reid (1988) asserted that the ‘first priority ... should be the attainment of universal scientific literacy’ (p.657). In proposing an outline for a curriculum which would work towards that goal, they listed eight features. At least three of these require some study of the history and sociology of science:

7. History and development of science and technology.
8. Study of science and scientific practice - philosophical and sociological considerations centering on scientific methods, the role and status of scientific theory and the activities of the community of scientists. (p.659)

In commenting on then current curricula in science, they noted some areas in which there might be improvement. The list included

4. Many courses make little, if any, attempt to deal with philosophical, historical, social, economic, moral and ethical issues.
5. There is too little integration of the sciences and of the sciences with other disciplines. (p.657).

Bybee, Ellis and Matthews (1992) considered that scientific and technological literacy must include an understanding and appreciation of science and technology in social and historical contexts. (p.327)

In the same journal issue as the one contributed to by Bybee et al., Good (1992), as editor, noted that scientific literacy ... includes more than accurate science concepts ... it also includes reasonable ideas about the history and nature of science. (p.325).

The connection between scientific literacy and the history of physics appears to have significant recent support, and this is explored more fully in Chapter 5.

2.2.5 History of Physics to Link the ‘Two Cultures’

Snow (1959) described the existence of two different groups of people who had such different outlooks and interests that they could barely communicate with each other. Scientists and those in the literary and humanities fields knew little of what each other did nor could they appreciate the significance of the endeavours of those in the other field. He saw that a broader education was the essential starting point in redressing this problem (which was more ingrained in the United Kingdom than in other large nations). This issue was taken up in the attempts which have been made to devise interdisciplinary courses such as that outlined by Lerner and Gosselin (1975): ‘We (aim) to eradicate the ‘two-cultures’ gap at the crucial point in its formation’ (p.13). Their approach was to examine how physics has developed and to draw comparisons between that intellectual pursuit and other modes of thought. They discussed the aims and methodologies of both physics and history. The course included much standard physics principally covered through an
historical context. This was done not only to serve the purpose just described but also because the authors felt that the historical approach could be beneficial in shedding light on concepts in physics which are often difficult for students to understand.

Neilsen and Thomsen (1990) also referred to the reasons for the emphasis given to the historical-philosophical dimension of physics in recent conferences. One of these involved an understanding of how physics can influence the wider society and how ‘the gap between the two cultures can be bridged from the science side’ (p.309).

### 2.2.6 Student Attitudes

Earlier reference has been made to the work of Ahlgren and Walberg (1973) regarding student attitudes to science and scientists. They, in turn, refer to the widely cited work by Mead and Metreaux (1957) on attitudes towards and images of scientists. Others such as Brush (1979) (not the Stephen Brush discussed in section 2.2.4), McDonald and Bridgstock (1982) and Schibeci (1986) have all written articles relating to the same concern. Each of these gave further references to studies carried out in the same area. All arrived at the same general set of recommendations - that science education should emphasize the ‘vital, fascinating human enterprise’, ‘the human dimension of science’, ‘the humanistic component’ and ‘humanitarianism’. The basis of these recommendations was that the scientific process should be portrayed more accurately, that ‘physics of a cultural kind is needed by almost everyone’ and that ‘the largely untapped audience of females makes the potential of the humanistic components even more attractive’.

Brush (1979), in particular, related her argument to the need to find some way of increasing enrolments in the physical sciences. She surveyed over one thousand first year university students in New England regarding their attitudes towards scientists and humanists in a variety of situations. She found that students who felt ‘closer in personal characteristics to their image of scientists’ were more disposed towards science courses. Consequently, among her conclusions were suggestions that ‘theories and hypotheses in science can be discussed as intriguing history’ (p.241).

Solomon (1991) supported this notion in her observation that ‘stories from the past can add a personal element to science which is often sadly lacking’ (p.101). In broad reference to the work of others she also pointed out the gender-balance-among-students
argument indicating that it has been found that ‘the (motivational) factor which most clearly differentiates male and female students is person interest’ (p.101).

Gauld (1977) recognized the motivational value for students in working within an historical perspective in the discussion of scientific theories (he also discussed other, equally important reasons such as those already mentioned in the above sections). Solomon (1991) has been another of the many who referred to the argument that ‘there is indeed much to recommend (the historical approach) for the motivation that it induces’ (p.97).

In offering strong criticism of the commonly-portrayed image of scientists, Home (1977) summarized many of the then innovations in science courses by saying that they seek to rid the scientist of his unfortunate image as a distant and rather alien figure in a starched white coat, steeped in the arcane knowledge displayed in our textbooks. (p.6).

While recognizing that these images can be dispelled by a variety of means, he was of the opinion that ‘an explicit H.P.S. component is a particularly effective way of tackling the problem’ (p.7).

Nielsen and Thomsen (1990) offered the ‘positive change in students’ attitudes’ as one of the reasons for the historical dimension in physics teaching as outlined at three history-in-physics conferences held during the 1980s.

2.2.7 Classroom Methodologies

Despite the range of contributions made to the history-in-physics debate over many years, there has been much less in the journals and books offering detailed descriptions or airing of ideas of how to actually go about planning a teaching course from such a perspective and what new skills are required by both the student and teacher. Some actual courses have been written, in whole or in part, from an historical standpoint. Such courses do not serve the same purpose as journal articles however, as they are not primarily intended to promote discussion or the investigation of new approaches.

Burdett (1989) recognized that the new aims for science education suggested by the National Science Curriculum in the UK in the late 1980s represented a challenge and perhaps even a threat to teachers, in that the traditional ‘didactic methods’ do not suffice and a ‘more participatory style of classroom management is needed’ (p. 181). This is particularly so in relation to the more philosophical aspects of science referred to in those aims. To this end, she reported on an approach based on role-playing a controversial event selected from the history of science. Working from a set of prepared notes and character descriptions for their particular scientist and his involvement in the issue, students prepared the outline of a play which they perform some days later. A debriefing took place at the conclusion of the simulation.

Rather than detailing a specific classroom development of a topic, Solomon (1989) briefly evaluated four different methods which may be adopted, in the light of the same changes in curriculum emphasis to which Burdett referred above. She cited the use of contemporary sources (scientists’ diaries or other writings), drama, small group discussion work and imaginative writing or art-work as potentially helpful approaches which avoid the dogmatic view of science so often implied by the traditional classroom setting.

Bonera et al. (1992) put forward a quite different approach to those mentioned above. They described experimental activities and computer simulations of historical experiments to assist in the diagnosis of student misconceptions. Their work related, in particular, to Galileo’s experiments with balls on an inclined plane and to Boyle’s experiments with gases.

Carson (1992) favoured the use of a narrative in which a particular episode is written up as if it were a contemporary ‘news item’ or short documentary relating some event in the history of science. His paper described what a meeting between John Dalton and Thomas Thomson in the summer of 1804 might have been like and included much of the conversation which might have taken place concerning the nature of matter.

And lastly Niedderer (1992) began with a strictly constructivist approach in recommending that the students’ current framework of understanding be established by discussion and investigative activities first. Then they examined some historical paper or problem relating to the concepts they have just been dealing with. He recognized that there
will often be limited parallels between student cognition and some earlier viewpoint held by scientists at some stage and recommended that those comparisons be pointed out. He described briefly how his approach could be applied to studies of how theories of dynamics and the photoelectric effect each were developed.

2.2.8 Other Arguments Relating to a Sociohistorical Approach

In addition to the above specific areas which have been put forward as reasons why an historical approach would be appropriate, many writers have argued for it from a range of other standpoints. These include the value of history in drawing together the purely academic and broadly societal aims of physics education, the sociology of science and the nature of the scientific enterprise, the evolution of science, and the contribution to the progress of society made by some of the great discoveries in science.

Ogden (1975) saw science education in the 1970s as having mutually exclusive purposes: it was either a component of a liberal education, or it was part of pre-professional training. He challenged the opinion that these directions assume that science courses should be of two different types. ‘If science instruction is to have a positive impact upon students it cannot continue along both paths’ (p.169). He suggested that a ‘possible solution to the problem may be found in the ‘historical’ or ‘sociohistorical’ approach to teaching’ (p.170).

Whitaker (1979) was one of the many who argued for the historical approach from the point of view that the sociology of science gives students an idea of how science is carried out. He also recommended that teachers should ‘make greater efforts to present physics as a living discipline, rather than as a completed structure of knowledge’ (p.242).

In addition to the cultural and attitudinal aspects referred to in sections b) and c), Nielsen and Thomsen (1990) also cited the ‘human activity’ angle, and the improved understanding of concepts as arguments in favour of the ‘historical-philosophical dimension in physics teaching’.

Krasilchik (1990) summarized the various arguments which have been put forward for the inclusion of history and philosophy of science into science curricula and recognized that it is one of the responsibilities of schools to assist in addressing these
views. Principally, her summary referred to the ‘comprehension of the evolution of science’, an understanding of ‘how the great discoveries contributed to the progress of humanity’, a ‘preparation for citizenship’, the motivation aspect and an appreciation of the epistemology of science (p.282).

A different line of argument altogether was adopted by Sequeira and Leite (1991) when they suggested that students’ understanding might benefit if teachers realized how hard some concepts were to establish and how long it took before some ideas were abandoned in the history of science, (their) knowledge about it becomes a tool to anticipate students’ difficulties in changing their alternative ideas towards the accepted ones. (p.53).

Admittedly, they were not necessarily arguing for students to be exposed to historical developments here; the recommendation was more relevant to teacher education, but nevertheless this was an area which must be dealt with before appropriate classroom approaches can be taken up.

Oldroyd (1977) summarized the ‘two main arguments ... advanced for the study of the history of science’ as follows:

to acquire an understanding of its actual theoretical and practical principles. Linked with this is the claim that the historical study is useful as a means whereby students may achieve an understanding of the methodology of science and the nature of the creative process or processes. And as a second major point it is asserted that a study of the history of science has an important role to play in a general humanistic programme of education. (p.11).

While proposing such arguments in favour of historical studies in science teaching, Oldroyd also described some of the counter arguments which have been put forward. He summarized these fairly simplistically along the following lines:

a study of the various ‘wrong turnings’ taken in the course of the history of science is a source of great confusion to pupils; ... there is so much to learn about the present situation in science that there cannot possibly be time to worry about its past also; and that the examination of a lot of old and worn-out theories is likely to prove exceedingly tiresome to restless teenagers and is hardly conducive to the successful training of students in contemporary science. (p.11).
Despite these negatives, he continued with a description and evaluation of instances where the history of science has been deliberately introduced into the secondary curriculum in Australia. His study (based on a questionnaire sent to 156 science departments in Sydney high schools) related specifically to chemistry courses, but his conclusions may well be valid in other disciplines within the science education field also. In these conclusions, he expressed disappointment in the gap which existed between the altruistic intent of the course designers and the actuality of what happens in the classroom, despite the good intentions of the teachers and their sympathy towards such an approach.

2.3 The Principal Contributors

2.3.1 Ernst Mach

Lederman, McComas and Matthews (1998) recognized the importance of Mach’s place in education when they observed that

For the past century - beginning with Mach in Germany … - understanding the nature of science has been an important goal of science instruction. (p.507)

Mach published a large number of papers throughout his academic life on a wide range of scientific and educational topics, but very little of it was specifically on his educational philosophy. Something of the flavour of his approach however can be gleaned from occasional comments in papers or transcripts of lectures. In a reprint of an 1893 lecture which he gave - On Instruction in the Classics and the Mathematically-Physical Sciences – Mach (1893/1986) indicated that

[he] should be satisfied if every young student could come in living contact with and pursue to their ultimate logical consequences merely a few mathematical or scientific discoveries. (p.367)

Matthews (1990), in writing a short summary of Mach’s educational ideas, related three reasons which Mach saw as arguments in favour of this approach. One of these indicated that Mach held similar views to those of the more recent educational psychologists Piaget and Ausubel:

[as with Ausubel ... he realized that instruction has to be relevant and understandable to those instructed. He believed in a vague form of the recapitulation thesis later
popularized by Piaget: that children’s intellectual growth closely followed that of the development of science. (p. 321)

He saw that students needed to be given instruction which is progressively built up with the students’ intellectual development in mind; he was of the opinion that this often closely matches the way in which scientific concepts develop historically. In addition, Mach saw his ‘genetic’ method (as he called it) as being of value in that it enabled the ‘fallibility of science’ to be demonstrated. A third benefit which Mach saw was in the way students could gain some understanding of sound scientific thinking.

All of this is not to say, however, that Mach was in favour of the study of the history of science per se; he advocated the approach essentially as a means of learning science, that is, as a means to an end. Blackmore (1972) pointed this out when he said of Mach:

... he meant teaching the ideas of earlier scientists to show the logical development of modern theories. He did not mean that the particular actions or thoughts of particular scientists should be taught or the historical factors that influenced why they thought as they did. ... Mach’s primary purpose in recommending a historical approach was to make contemporary science more understandable, not to make past science more understandable. (p. 133)

Blackmore (1972) quoted Mach as believing that the fundamental goal of education was to “satisfy human ‘biological needs’ in the most ‘economical’ way possible” (p.132). Mach, according to Blackmore, was not suggesting that the teacher should get to the ‘heart’ of the topic as quickly as possible - this would not guarantee understanding as the student would, in all probability, not be cognitively prepared to accept the subject matter. He equated ‘economical’ with ‘efficient’, that is, a balance between time taken to convey a concept and ensuring that the aim of understanding is achieved. Consequently, he (Mach) recommended that the teacher should begin instruction with visual examples and imaginative demonstration, slowly evolving into a historical presentation of the subject. Only when the student mastered the problem in its concrete and historical development was he capable of adequately understanding general and abstract solutions to the problem (Blackmore, p.133).
Mach was not as attentive to historical detail as he might have been and he was somewhat Whiggish (see Chapter 7, section 7.2, and also in Hall, 1983) in his treatment, partly because his prime purpose in using history was to improve understanding of present theories rather than in embarking on a careful study of the past. Bluh (1970) observed:

Mach wanted to write not as a historian of science, but as a critical physicist whose work arose from a didactic purpose. He did not write the Mechanics to set the history of mechanics right, but to set Newtonian physics right; not to discuss Newton’s achievement in its historical meaning, but in its scientific meaning. He tried to deduce ... the development of certain branches of physics along logical, not chronological lines.  
(p. 11)

Despite this, however, Mach's reputation as a user of physics history in physics education is widely known and respected. This is illustrated in the comment made by Besso in 1946 in a letter to Einstein and quoted by Holton (1970):

As far as history of science is concerned, it appears to me that Mach stands at the center of the development of the last 50 or 70 years. (p. 169)

Mach deserves to be counted as one of those who made a significant contribution to the debate encouraging the involvement of physics history in the teaching of physics generally, even though his approach was somewhat different from more recently expressed views. These later ones have grown, in part, out of changes which have arisen in the philosophical understandings of the nature of science during recent decades. Some of these will be discussed in more detail in Chapter 4.

2.3.2 James Conant

The other principal early worker in implementing an historical approach to physics education was James Conant. He was a key figure in the teaching of science at Harvard University during the middle decades of the twentieth century. In his Terry Lectures delivered at Yale University in 1946, Conant (1951) indicated that he aimed to “give a better understanding of science to those who have no intention of being scientists” (p. v). A little further on he referred to his earlier text, On Understanding Science – An Historical Approach (Conant, 1947), and indicated the twofold task he had for that text:
to give the general reader some understanding of the methods of science and to outline for the college teacher how one type of instruction might possibly be carried out (p. vi).

His teaching was based on a ‘case studies’ approach, and he published these in a book entitled *Harvard Case Histories in Experimental Science*. The fact that he was primarily a teacher (in the fullest sense of the word) is brought out in the way he was continually interested to know how effective his presentations were, and regularly implemented changes in his approach when necessary. For instance, in the preface to *Science and Common Sense*, Conant (1951) pointed out that

> further discussions of my proposals for teaching science to nonscientists would now have to consider what has happened in the last five years ... in the teaching of college science (p. vi).

and in reference to his undergraduate lectures:

> both the ideas and the mode of presentation have been more than once subject to drastic change. This book, therefore, reflects the impact of student on teacher. To a far greater degree it reflects the impact of a group of teachers on the author. (p. vii).

He then proceeded to explain how he held weekly meetings with colleagues to discuss course progress and to propose new ideas. This also gives some insight into another aspect of Conant’s work. It shows how his importance derives not only from the programs and courses he himself produced, but also from the marked influence he had in the development of a generation of physicists, physics historians, philosophers and physics educators. This can be seen at the conclusion of the preface to his *Science and Common Sense* text where he acknowledged the assistance provided by colleagues in the preparation of that book. Among the names mentioned are people who have since become significant in the scientific and educational world in their own right; people such as Fletcher Watson, Thomas Kuhn, and “a learned young historian of science” I. Bernard Cohen. In mutual acknowledgement, Kuhn (1970) reported:

> (i)t was James B. Conant, then president of Harvard University, who first introduced me to the history of science and thus initiated my transformation in my conception of the nature of scientific advance. Ever since that process began, he has been generous of his ideas, criticisms, and time .... (p. xi)
Clearly, Conant has been one of the significant contributors to the “history of physics in teaching physics” debate.

2.3.3 **Gerald Holton**

Another contributor who has been influential over many decades in describing the value of an historical approach is Gerald Holton, who began working at Harvard in the early 1950s. Holton was one of three people (the others were F. James Rutherford and Fletcher G. Watson) who, in 1964, initiated the Harvard *Project Physics Course* (PPC) for secondary school students. Holton’s aims and methodology for science education are evident in that course and are also described in various articles in the literature. Regarding their approach to the subject matter, Holton (1978) said that “a humanistic conception of science (was) really at the heart of the program” (pp.289-290) and “a student should not be deprived of ... seeing the historical connections ... of physical science” (p. 290). In addition, he saw such an approach as having another important function:

> (w)hether or not they will become scientists, it is essential that students have a chance to see the full vision of science and thereby be protected from narrow blinkers or naive euphoria just as much from the false and hostile ideas about science and scientists which have been spreading in the past three decades, particularly in industrial societies.  (p.290)

Regarding the need to acquaint as many students as possible (especially females) with that broad view of science, Holton believed that

> (w)e must continue to try to reach a larger proportion of students than would otherwise be taking the initiative to enroll in physics courses as part of their total education. We have found that a humanistic approach to science can enlarge the pool of prospective students. Thus the proportion of young women enrolled in the Project Physics Course is nationally about twice as large as in the traditional physics course.  (pp.290-291)

Holton lamented the fact that physics teaching has been directed at the few percent of students who are of higher academic ability and who intend to follow a career in the physical sciences. He recognized that the group of students which the PPC aims at is nowhere near as homogeneous as traditional physics courses have been. To cater to this wider range, this course had to take into account the fact that

> (s)ome students will excel in the mathematical or laboratory part, others in the more verbal reports, perhaps connected with their interest in social science or history. (p. 293)
Partly as a consequence of this, he also recognized the need to try different teaching styles, for instance using a ‘group’ approach in which each member of the group is responsible for a different aspect of the topic under consideration, and their test assessment is based on the average mark of all members of the group. This and other PPC methodologies had to be different from those of traditional courses because, he said,

we wanted to illustrate how physical science actually developed as well as the humanistic and societal impact of science (p. 294).

Holton referred to a comparative study of students’ attitudes to physics as a result of their studying one of a number of different physics courses, the PPC being among them. This study, based on a survey of ninety-six students by Ahlgren and Walberg (1973), found that attitudes were significantly more positive among students who took the PPC because of its more historical, philosophical and less mathematical approach. The writers concluded that

(i)t seems that the image of physics tends to have strong negative components, that curriculum can affect its image, and that its image is related to interest in studying it. The relation of the science to people - through being beneficial, social, artistic and humanitarian - seems to offer the best chance to regain lost interest and a lost audience. (p. 189)

However, Glass (1971) was somewhat more doubtful of the success of the PPC to fully implement his goals of science education. He cited, in his editorial in Science, that there are

two functions of science education: the one, the technical and empirical, being to transmit and extend the knowledge requisite of human power; the other, the philosophical, being to develop as understanding of man’s place in the universe. (p. 851)

This appears to be the reference point for his observation that

(i)t is undeniable that our science curricula have in part failed, even the newest and best of them, to deal sufficiently with the role of science in the making of human culture, with the problems of the present world and the fair or dread vision of the future of man. (p. 851)

This observation, however, seems to be based only on his personal opinion rather than on any research evidence; nevertheless, Ahlgren and Walberg, having surveyed
student and teacher attitudes towards science, were in sympathy with his view generally, although not with regard to the PPC.

The Project Physics Course was not Holton’s first venture into the field of history of science in science education, although it was his first attempt to use that approach on a large scale secondary school program. He had always used that approach in his tertiary teaching courses, especially when these were directed towards the non-science majors. He was attempting to impart an understanding of science to those who were not going to spend their careers in that field. To that extent, he was aiming at an audience similar to many secondary school classes in physics or science. He did not see his approach as necessarily being easier than specialist courses, it merely involved a different emphasis in content and direction. Holton (1952) explained in the introduction to Introduction to Concepts and Theories in Physical Science that the focus of that text was on ‘the subject matter of physical science’, but that there were also ‘other aims - above all the presentation of science as experience, as an integrated and exciting intellectual adventure’ (p. xiii). Further on, he stated that:

on their own merits, the inclusion of history and of philosophy of science is justified in an introductory course for the nonspecialist. (p. xiv)

and he saw three reasons for adopting the history and philosophy of science approach:

[firstly, it] prepare[d] the appropriate setting in which a particular idea came to have meaning and importance; … [secondly, it] provide[d] insight into the sources, motivations, and methods of approach of the founders of science; …[and thirdly it] present[ed] science as one facet of the great quest for knowledge (which is so highly regarded by society). (p. xv)

He quoted extensively from Whitehead’s 1945 Report on General Education in a Free Society, pointing out that the latter’s Report described the need for a course similar to the one which he, Holton, favoured. Holton (1952) referred to Whitehead’s opinion that science is not just a technical pursuit but that it also involves conceptual interrelations, a world-view, and a view of the nature of man and knowledge, which together constitute the philosophy of science; a history which forms a continuous and important segment of all human history (p. xiv).
Further on, he indicated that the course
will contain much solid scientific content ...(and there will also be an) emphasis on
historical development ... not merely a humanistic garnishing ... (but) an attempt should
be made to teach science as part of the total intellectual and historical process (p. xvi).

Although it is written primarily for the non-specialist science student, Holton also
saw his course as being of significant value in a strictly technical course so that students
will not become too narrow-minded in their view of science in the wider scheme of things.
His text, *Concepts and Theories*, appears very similar in development to the later PPC in
that historical material is interwoven throughout in such a way that it is neither a straight
history of science text nor a traditional physics book.

In a later statement, Holton (1975) summarized his ‘credo’ regarding science
teaching. He considered that an educated person should know something of the main
concepts and theories of science for four reasons: to appreciate our cultural background, to
provide career opportunities, to enable a person to act as an intelligent citizen and ‘to
make one truly *sane*’. He also continued with his goal of bringing some understanding of
the physical sciences to those who may have otherwise had no contact with it: ‘to tell what
we know ..., how one came to accept it ... and to tell of the effects of and by science’ (p. 103). In his courses he therefore covered the main scientific theories and incorporated
within them ‘materials introduced at chosen points to explain the epistemological, the
historical, the societal, and humanistic contexts of scientific work’ (p. 103).

Mach’s work and reputation notwithstanding, it could well be said that Conant and
Holton are the founders of the historical approach to science teaching, at least in recent
times.

2.3.4 *Stephen Brush*

Among those who have written papers on the fundamental arguments related to the
historical approach, Stephen Brush is one who stands out as being a notable protagonist in
the debate over many decades. For example, as Russell (1981) observed:

Brush ... stands out as the historian of science who has developed detailed commentaries
on the uses of history in teaching science. (p.52)
He began his academic studies at Harvard in the early 1950s when this was one of the few institutions which had a strong history of science group of academics. By the mid 1960s he had returned to Harvard as a lecturer and joined the fledgling group which had, in 1964, begun work with the PPC team. Since then he has written much, has organized conferences and edited journals, all with the view to advancing the cause of the socio-historical approach.

Brush (1969) contrasted the *traditional* method of teaching physics with a new *historical* method of teaching. He used the term *logical* to describe the former approach although not intending to imply the axiomatic meaning of the word. In admitting that some history may have been included in the former approaches, he considered that this was often so superficial as to be worthless or else demonstrably wrong. He wondered if a student learning in the traditional method would be any less competent in doing and applying science if he were told that ‘Darwin proposed $F = ma$ in 213 B.C. and that Boyle first determined the speed of light in 1947’ (p.272). Brush asserted that ‘a historical method must go beyond names and dates if it is to be of any value’ (p.272).

He divided the history of science in education into three areas: general education (high school oriented), technical education (essentially tertiary level courses designed for science-major students), and ‘educational’ education (related to teacher education). Regarding the first category (which is the area of principal concern of this thesis), Brush sees the PPC as the ‘first major curriculum development which includes substantial attention to the history of science as part of a science course at the high school level’ (p. 272). He regarded this approach as being of value because ‘students need to learn the importance of science in the development of Western civilization, and the relation between science and other subjects’ (p. 272).

In an obvious reference to *The Two Cultures* (Snow, 1964), Brush (1969) saw that it may be possible for the history of science (to) be a bridge between the sciences and the humanities’ (p.272), and that ‘a science-shy student will be more interested in science if it is presented from a historical viewpoint, with emphasis on people rather than equations’ (p.272). As Snow (1964) himself had observed, during his time at Cambridge University, he was constantly ‘moving among two groups ... who had almost ceased to communicate
at all’ (p. 2), and, further on, ‘I believe the intellectual life of the whole western society is increasingly being split into two polar groups’ (p. 3). Commenting on this state of affairs, Snow bluntly stated ‘(i)t is all destructive’. (p. 5)

Regarding those often-revered characteristics the ‘scientific method’ and the ‘hypothetico-deductive’ process, Brush (1969) also pointed out that a ‘detailed examination of case histories might induce a skeptical attitude’ (p. 278). He recognized that the implementation of an historical approach is not easy for many reasons (inadequate teacher training, limited resources, difficulty in deciding what to include in a course, and the time-consuming nature of primary research) and recommended that, for appropriate teacher preparation:

The best type of course in the history of science for a science teacher is … a workshop-seminar in which each person investigates one or two case histories in considerable detail. ... The goal of the course would be to discover how science really works by examining actual discoveries. (pp.278-279).

Later, in a widely-cited paper, ‘Should the History of Science be Rated X?’, Brush (1974) examined contemporary arguments for and against the use of history of science in science education. He indicated that there is little point in a teacher adopting such an approach if his intention is ‘to indoctrinate his students in the traditional role of the scientist as a neutral fact finder’, but for those ‘who want to counteract the dogmatism of the textbooks and convey some of the understanding of science as an activity that cannot be divorced from metaphysical or esthetic considerations’ (p. 1170) then there may be some value in the history of science. He used specific historical examples to illustrate the subjectivity of science, and the way its development is often poorly reported in secondary sources. He noted that teachers must become aware of the widespread skepticism about the objectivity which is often portrayed as being a characteristic of science.

He was somewhat cautious in his support for the ‘new approach to the history of science’ and concluded that

if [it] really does give a more realistic picture of the behaviour of scientists, perhaps it has a “redeeming social significance”. (his emphasis) (p. 1171)
In a later article, Brush (1989) pointed out that a common recommendation for improving the ‘general understanding of science among our citizens’ is to use the history of science. He considered that the essence of a historical approach is not merely to assert the conclusions but to show how they were reached and what alternatives were plausibly advocated. (p. 61).

He devoted some time to pointing out the aims of the humanistically oriented PPC and the success which that course experienced in changing students attitudes towards physics and improving their understanding of the relationships among science, technology and society without altering their ‘acquisition of scientific knowledge’ (p. 62). There are three features which Brush suggested should be present in a course which aims to improve students’ understanding of the nature of science via an examination of historical material: an examination of the broad philosophical questions raised in science (for example, the relationships between science and the Church, and determinism), a demonstration of how science can be useful even though it is a human endeavour and therefore subject to human limitations and failings, and a commitment to show that women and other minority groups have played an important part of the development of science (and therefore appropriate role models can be presented).

2.3.5 **Michael Matthews**

A more recent ‘standard-bearer’ in the literature for the cause of history of science is Michael Matthews. In addition to his contributions to journals, he has also taken a leading role in his organization of conferences, establishment of interest groups and editing and introducing new journals. Among many notable contributions he has made to the ‘history in science’ debate, one of the more significant in terms of being all-encompassing in its examination of the arguments, related issues and curriculum developments, has been his ‘A role for history and philosophy in science teaching’ (Matthews, 1988, and reprinted in Matthews & Winchester, 1989). An indication of the breadth of the article can be gained from the following summary. In that work, he discussed (i) the changed emphasis in learning theory in science education from the ‘inquiry’ based ideas which inspired much of science teaching in the later 1960s and 1970s to the ‘Piagetian view that (students’’) intuitive beliefs mirror earlier stages in the
history of science’ (1988, p. 68) and the constructivism which is related to and derived from this theory; (ii) the calls for change in curriculum directions by government bodies in both England and the U.S.A. during the 1980s; (iii) some of the more notable educationists and historians who have argued for some form of historical approach and the Harvard Project Physics Course which resulted from some of this work; (iv) the benefits of the historical approach as seen by a number of other contributors; (v) some of the doubts which have been cast over the teaching of history as it actually happened, especially in the views expressed by Kuhn (1970); (vi) the need for philosophers of science to become more involved in broadening the teacher’s outlook of science, in the expectation that this will provide a more stimulating classroom environment and greater learning; and, (vii) a brief conclusion indicating some of the changes which must take place before an effective History and Philosophy of Science approach can be implemented in science courses. This paper by Matthews was later expanded to a much more detailed discussion of essentially the same issues in Matthews (1992). His views have been further elaborated in more recent texts (Matthews, 1994 and 2000).

Matthews (1988) described six benefits which are often mentioned in the adoption of a historical approach in science teaching - the opportunity to bridge the ‘Two Cultures’ gap; increased understanding of the subject matter; greater interest in the subject; improved critical thinking; greater involvement of girls; and the improvement of science’s image by introducing a more human aspect. In addition to these, Matthews (1992) included a further benefit in relation to history, philosophy and sociology of science:

[it] can improve teacher training by assisting the development of a richer and more authentic epistemology of science (p. 12).

In that same article, he discussed the problem which students experience in coming to grips with the idealizations of science, particularly those which are in apparent disagreement with observation and experience. An examination of the way in which those idealizations were arrived at can be of assistance both to the teacher in being aware of the difficulties which the student has in accepting idealizations and to the student in understanding that the idealizations are not immediately obvious (Matthews referred to Duhem’s observation that they are the accumulated result of the work of geniuses over thousands of years!).
One of the main additions which Matthews (1992) made in his later paper involved a discussion of six issues which he saw as relevant to the science education debate (although his thinking was not necessarily positive in relation to each of the views): ‘Feminism, Constructivism, Ethics, Metaphysics, Idealization, and Rationality’ (p. 33). Feminism is raised as a question relating both to the low numbers of women involved in science studies and to the alleged masculinity of the ‘very epistemology of western science’. The proponents of Constructivism are challenged to address issues such as the contribution which the social dimension makes towards the growth of knowledge, the ‘criteria for adequacy of student conceptions’ (p. 34) and the need for students (at least those going on to a career in science) to, at some point, adopt the paradigms and methodologies of the scientific community despite, perhaps, the views they might have been lead to construct for themselves. Science teachers can benefit from the deliberations of philosophers in relation to the many socially responsible issues which are being raised more and more often. The relationships between religion and science over the centuries must be examined in developing a full understanding of the epistemology of science. In addition to comments Matthews made elsewhere, he also argued in his ‘Topical Questions’ section that teachers should be aware of the non-empirical way in which many of the common idealizations arose when they were developed (for example, the Galilean/Newtonian generalizations). The rationality of how scientific theories develop and change is another of the issues which, Matthews contended, should claim the attention of science teachers. He concluded both papers with a description of what is required for the success of the new directions currently emerging in science education: involvement of historians, philosophers and science educators in the incorporation of HPS courses in science teacher training courses and in in-service education, the preparation of classroom materials, further research, and critical examination of texts and programs.

2.4 Conclusions

There has been on-going and increasingly detailed discussion, during the latter half of the twentieth century in particular, surrounding the ‘history of physics in physics education’ issue. The arguments in its favour have become more diverse as the needs of society and the consequent responsibilities imposed on education have become more complex. Although a number of separate early sources can be identified, the Harvard
department of History and Philosophy of Science is a significant reference point for many later contributors and developments; James Conant being the central figure in this. Many academics and educational practitioners have been active in the debate since then, with Holton, Brush and Matthews being the most influential.

Considering the extent of the discussion, there has been relatively little in the way of new curriculum design appropriate to the approach. A number of explanations could be provided for this, among them, the range of objectives proposed for an historical approach: different purposes will require different methodologies. Realistic, wide-ranging and socially responsible objectives for physics education need to be decided upon and further research in the application of educational techniques, especially those which have been developed for the humanities disciplines, needs to be undertaken. The end results of these will indicate the breadth of application and likely effectiveness of an historical context within physics.

The increasing frequency during the 1980s and 1990s of international conferences concerning the history of physics in science teaching, as well as new journals such as Science and Education, may provide a focus for clarifying these fundamental precursors to curriculum design and teaching approaches. This research, based on the links between the nature of science, scientific literacy and the historical approach, is an attempt to fill the curriculum design gap.

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CHAPTER 3

CHANGING CONCEPTIONS OF SCIENTIFIC LITERACY

3.1 Introduction

The goal of science education is frequently stated as the achievement of scientific literacy. Although the concept was introduced in the 1950s, during the last twenty years there has been a renewed emphasis by science educators and others in debates surrounding scientific literacy. In comparison to older and more traditional views, this re-conception draws a much broader picture of what science education should involve and to whom it should be directed. These recent discussions have produced a range of new descriptions for the goals of science education.

In this chapter, an examination of the conceptions of scientific literacy during the second half of the twentieth century is presented, thereby highlighting the re-conception which has taken place during the last twenty years of that period. The focus will be on developed western society, which has very different outcomes and expectations for scientific literacy compared with, say, developing African nations (for example, see Mulleme, 1996) or “the citizens of China or Bangladesh” (Jenkins, 1990, p.48). The underlying purpose of this, in the context of this thesis, is to establish a clear connection between scientific literacy and a study of physics (and science) which is based on a historical approach.

Either as a slogan or as a goal, the term “scientific literacy” has been in use for some time. The history of such usage has been discussed in some detail in a discussion paper by Roberts (1983) who suggests that “the phrase seems to have originated in the 1950s” (p.20). Both broad and comparatively narrow meanings have been applied to it, to the point that it may be argued that the term itself is of limited usefulness. Raizen (1991) observed that “there is no unanimity on what represents scientific literacy” (p.35). Lawwill and Teates (1992) commented on the widespread use of the “literacy” term itself - “[h]as not the significance and meaning of this word become greatly exaggerated?” (p.29). The latter two authors quoted Kintgen (1988) who wondered whether the word is used because it is perceived as “catchier” than “knowledge” or “competence”. The reason for the use of the word may be because of the emotions generated by implying that the negative (illiteracy) of the term might be
the result of no effort being made to achieve the goals seen as important by whichever individual or group uses the word. In this vein, Graubard (1983) considered the word “deliberately chosen, principally to sound a political tocsin” (p.233). Meanings and word usage aside, the heart of the matter should be what it is that defines the content and purpose of science education courses. This will be indicated by the desired educational and societal outcomes suggested by proponents of “scientific literacy”. Despite any shortcomings in meaning, the term will nevertheless be used throughout this chapter, while retaining an awareness of the emotive and political undercurrents which may be attached to it.

The discussion begins with an examination of an analysis by Pella, O’Hearn and Gale (1966) of meanings of scientific literacy which appeared in the literature of the 1950s and early 1960s. Then a more detailed investigation is undertaken to uncover the recent (since about 1980) meanings of the term, particularly as highlighted by Roberts (1983), Arons (1983), the American Association for the Advancement of Science (1989 & 1993), and Jenkins (1990, 1992, 1994 and 1995). Associated with the scientific literacy notion are a number of other movements, usually having a more specific focus. These include Science For All, the Public Understanding of Science, Social Responsibility in Science, the Science-Technology-Society movement, and Feminism.

The chapter concludes by considering the nature of science theme which runs through so much of the discussion of scientific literacy, not as a definition but as one of its key features.

3.2 Scientific Literacy of the Fifties and Sixties
3.2.1 The Key Referents of Pella, O’Hearn & Gale

It is possible to obtain an overview of conceptions of scientific literacy held during the 1950s and early 1960s from an analysis undertaken by Pella, O’Hearn and Gale (1966). They studied one hundred publications by a range of authors. The publications included eighteen books such as *The Sociology of Science* by Barber and Hirsch, *The Common Sense of Science* by Bronowski and the famous *The Two Cultures: A Second Look* by Snow. The 82 articles were drawn from journals such as *Science, Physics Today, American Scientist* and the *Bulletin of Atomic Scientists*. The writers of those included J. Conant, M. Polanyi, J. Schwab and G. Holton. From their
investigation, Pella et al. found three principal goals for science education - as a preparation for future scientists, as background for future workers in medical and technological fields, and as an essential component of effective citizenship. They undertook a detailed investigation of what the then current impressions were of the notion of scientific literacy which was seen as the key to the “effective citizenship” goal. Notably then, they saw vocational goals as separate from the literacy imperative. Many others have made a similar distinction (for example, see Fensham, 1985, and Ziman, 1980). In the publications analysed, Pella et al. found six key referents:

The scientifically literate individual presently is characterized as one with an understanding of the (a) basic concepts in science, (b) nature of science, (c) ethics that control the scientist in his work, (d) interrelationships of science and society, (e) interrelationships of science and the humanities and (f) differences between science and technology. (p.206)

The analysis by Pella et al. indicated that the interrelationships between science and society, the ethics of science, and the nature of science were considered to be more important, occurring in over half of the articles analysed, than the other areas - none of the lowest three referents occurred in more than one quarter of the articles. Of interest is that conceptual knowledge was in that lower group - it was not often referred to as a component of scientific literacy.

The scope of those key referents, and the indicators suggesting one or other of them, in the articles examined by Pella can be summarised as:

Conceptual Knowledge: Because of the relationship between scientific literacy and effective citizenship, the references made to conceptual knowledge in the works studied by Pella et al. were generally suggestive of the connections between that knowledge and areas external to science - “the lay public”, “freedom from the slavery of the supernatural” and “controversial topics” were all terms used in relation to the conceptual knowledge referent. Of particular interest with respect to this thesis is one of the “typical statements” they found in relation to knowledge of scientific concepts:

Historic and cultural roots of science should be a part of the public’s understanding of science. (p.204)
Nature of Science: Pella et al. observed a range of understandings of this concept from “science is a body of knowledge” to “science is an idea developing activity”, with the more common interpretation being closer to the latter. Other characteristics included reference to a multiplicity of methods of science and the progress of science as a “series of approximations”.

Ethics of Science: The ethics referent included such terms as “the truth with respect to the world of matter and energy”, “objective truth and the rules for discovering it”, “knowledge of the physical and biological world without respect to any present or future good or evil”, and “induction of general laws”. Also, notions such as “a wider appreciation of the ethical implications of science for the common good”, the need to “judge and interpret the statements and values of scientists”, and the importance of scientists showing leadership in communicating clearly to the public were used by Pella et al. in deciding whether the ethics of science was referred to by the writers whose works they analysed.

Science and Society: Typical statements indicated the need for awareness of the centrality of science and technology as a causative agent in societal change, the dependence of science on society for resources, the liberating power of science with respect to magic and superstition, and the need for the public to appreciate the limitations of science and technology.

Science and Humanities: The articles studied by Pella et al. suggested that the connection between science and humanities could be illustrated in the cultural changes which science produces, and that “learning science (should be seen) as part of the American cultural heritage”.

Science and Technology: Lastly, differences between science and technology in the articles studied included an understanding of the differences in their “short and long run purposes”, the use of technology to bring the non-scientist in touch with science, and the mutual influence which one area has on developments in the other.
Although this survey undertaken by Pella et al. uncovered a wide-ranging conception of scientific literacy during that era, their summary nevertheless represents an eclectic view of opinions held at the time. They noted that over half of the articles made reference to only one or two of the six referents, and only two of the one hundred works included as many as five referents. Despite the apparent objectivity implied by their numerical statement of frequencies of occurrence of various notions, their analysis still required them to make some subjective interpretation of the messages communicated by each of the writers. Accordingly, their figures may, if anything, be an understatement of the picture at that time, as it is more likely that a referent may have been missed rather than counting one which was not intended by the writer. By way of example to illustrate this point, the paper by Hurd (1958) is often used as a key document in discussions of the beginnings of the scientific literacy imperative during the 1950s. According to Pella et al., Hurd’s contribution touched on four of the six principal referents, omitting “conceptual knowledge” and “science and technology”. However Hurd did actually acknowledge at least one of these as a component of scientific literacy:

> There is a tremendous volume of scientific knowledge and concepts from which it is necessary to choose a small per cent to form the content of courses. (p. 15)

This provides an example of possible underestimation by Pella of the number of referents which would be attributable to an author who was attempting to outline the scope of scientific literacy. Overall, it can be said of the views of scientific literacy during the 1950s, that although a broad range of characteristics had been proposed, such breadth was not often found in the writings of any one author.

### 3.2.2 A Narrow Conception of Scientific Literacy?

The analysis by Pella et al. portrayed a moderately liberal conception of scientific literacy during the 1950s and 1960s. Miller (1983) has suggested that a narrower interpretation of the term existed in that era. He referred to surveys carried out on precollegiate students’ scientific knowledge in the early 1960s. These investigations, according to Miller, were based on an early interpretation of the term scientific literacy: “an understanding of the norms of science and knowledge of major scientific constructs” (p. 31). Jackson (1983) similarly observed that the “chief complaint [about the “new” curricula of the 1950s and 1960s] was that most of the high-school curricula were designed for college-bound students ... and principally
those headed for scientific careers” (p. 153). A multi-national study of secondary and tertiary physics courses carried out by UNESCO (1966) concluded, in relation to secondary-school physics:

In their content and organization they anticipate university work ... even to the extent in some countries of being formally a part of a spiral educational process. (p. 39)

This interpretation of scientific literacy suggested by Miller is consistent with the content and emphasis of many science texts and courses of that time. Matthews (1994) referred to the “economistic view of education (which) promotes a narrow conception of scientific literacy” (p.32). He recalls the Physical Science Study Committee’s Physics text which concentrated on the “conceptual structure of physics (in which) applied material was almost totally absent” (p.16). With reference to a broader subject base than just physics, Matthews observed that, during the 1950s, the “National Science Foundation was instrumental in the transformation of school science into proto-university science” (p.16). This has often been the approach taken to science education - most notably during the 1950s and 1960s - when courses were “up-dated” in response to the perceived need to maintain military and economic supremacy (particularly in the United States) through scientific and technological development. Economic progress was a clear aim of educational reforms, but military supremacy, while not so explicitly stated, was a more fundamental goal. Raizen (1991) discussed the connections between scientific institutions, education, and technological development. The links between those three are indicated by the formation in the US in 1958 of the National Defense Education Act.

The observations of Matthews and Raizen regarding what actually happened in the 1950s stand in contrast to the opinions of scientific literacy uncovered by Pella in relation to that period. The views analysed by Pella were not those of people who designed school curricula, or, if they were, then, according to Matthews and Raizen, their more liberal views of science education were not reflected in the science of the classroom.

3..2.3 Aims & Course Content in the 1960s

The aims and approach to science teaching in the 1960s can be compared by examining the Association for Science Education (1967) secondary science teachers’ handbook. Quoting in part from the general policy statement drawn up by the
Association for Science Education in England two years earlier, this book indicated that the following could be taken as guiding principles for science education:

Present “scientific illiteracy” is, in part, due to a lack of factual knowledge, but is more the result of a lack of understanding of the basic nature and aims of science. Science should be recognized - and taught - as a major human activity which explores the realm of human experience (and) creates a coherent system of knowledge. As a human quest for Truth - and it is much more subjectively human than is often realized - science is concerned with basic values and is, indeed, one of the humanities.

It follows that schools have the duty of presenting science as part of our cultural and humanistic heritage to be taught in harmony with, not in opposition to, the various art subjects. ...We recognize that an adequate supply of scientists and technologists is needed ... but we stress the cultural aim here. (p. 1-2)

The general tenor of these aims suggests a broader conception of scientific literacy. However, the bulk of the text outlined in detail the teaching material and approach to be followed (down to specimen lesson plans). This consisted entirely of descriptions of practical work such as “animal or plant observations” or “chemical preparation”, the setting up of apparatus to demonstrate particular scientific principles and so on. “General principles should follow from the facts” (p.3, my emphasis). In an apparent contradiction to the stated aims, nowhere is there any reference to the place of science within a broader culture, the human aspects of science or its subjectivity. Despite the progressive nature of those aims, proposals for what was actually taught were quite different.

In the United States at about the same time, teachers were given similarly ambiguous messages from a text edited by Washton (1967). References were made to social responsibility, changing technology, science implications and the community, and science values. General guides to lesson plan approaches included not only fact and concept-related ideas but also hypothesis testing, attitude development (for example, open-mindedness and intellectual honesty) and an appreciation of the contribution of scientists. However, the actual syllabus guides to the various disciplines listed only the “traditional” content and concept-centred topics (although each main area concluded with a “Vocations and Avocations” section in relation to the discipline just studied). Here again, there is little relationship between the broader view of science, and what is actually recommended for the classroom. The more
altruistic goals seem to be given more as a justification for the teaching of science rather than as a direction for what should be taught.

Thus, while there were certainly indications of more liberal views for the aims of science education (as illustrated by Pella’s analysis), much of the curriculum which was being revised and set at that time was of the narrow, content-oriented type. An example of this in Australia was the New South Wales-based text by Messel (1964) and about which criticisms were raised by Cross (1995). Accordingly, such a text could be taken as implying an acceptable notion of what science education should be during the 1950s and 1960s (the use of the term “scientific literacy” in reference to such courses seems to be applying the concept too widely and to areas for which it was not intended). Nevertheless there were notable exceptions to those traditional courses, such as the tertiary courses designed by Conant at Harvard in the late 1940s and 1950s (based on Conant, 1957), and emanating from the same institution in the later 1960s was the Harvard Project Physics course for senior secondary school physics. Both of these developed the notion of science as a human activity and drew significantly on historical analyses.

3.3 Recent Conceptions of Scientific Literacy

3.3.1 A New Emphasis

Since the late 1970s and early 1980s, there has been a qualitative change in the nature of discussions surrounding the notion of scientific literacy. Raizen (1991) observed that “the reforms (in U.S. science education) started from a low point of support for science education in the early ‘80s” (p.35). Since then, there has been a significant and on-going debate surrounding the importance of scientific literacy, its meaning, and the need for greater efforts to be made in adopting a liberal interpretation of it as the focus of secondary school science courses.

Attempts to define the term have been many and, as Raizen noted, “there is no unanimity on what represents scientific literacy” (op. cit., p.35). In the one statement, he offered both a prediction and a challenge (p.36):

(u)ntil the different conceptions of scientific literacy can be clarified and appropriately modeled, schools are unlikely to change traditional practice.

Accordingly, it is appropriate to examine some of the attempts which have been made to “clarify” the term and to determine the common ground among them.
3.3.2 **The Seven Curriculum Emphases of Roberts**

By way of comparison to Pella et al., Roberts (1983) talked of seven “Curriculum Emphases for Science Education”:

- Everyday Coping, ... Structure of Science, ... Science Technology and Decisions, ...
- Scientific Skill Development, ... Correct Explanations, ... Self as Explainer, ... and
- Solid Foundation. (p. 13)

The first of these was used by Roberts to refer to applications of science to situations likely to be commonly encountered by students. “Structure” related to the intellectual enterprise of science. The third area involved the limitations of science, its strengths, the connections between science and technology, and the use of those disciplines to assist in making decisions about whether to develop or implement a particular technology. Skill development referred to the conceptual and manipulative skills associated with experimenting and investigating. Correct explanations clearly was focussed on concept development and theory structure. Self as Explainer emphasised the personal and cultural contexts. The last of Roberts’ emphases concerned the importance of continuity in building up a body of knowledge through secondary school and into university.

These emphases can be contrasted with the six referents which Pella et al. extracted from their analysis of documents. The first has no clear comparison with Pella’s list; Roberts’ “Structure” is roughly equivalent to “Nature”; his third (“Decisions”) could be linked with Pella’s “Ethics”; “Correct Explanations” would relate to “Conceptual Knowledge”; “Skill Development” has no equivalent in Pella’s list; nor do Roberts’ last two categories. Some of Roberts’ seven may actually relate to the first two of Pella’s goals for science education - the vocationally-oriented goals. All of this demonstrates the breadth of interpretation in meaning of the scientific literacy term during this period.

Roberts suggested that there should be some balance in focussing on his seven areas throughout a child’s education. His analysis of actual science programs which purported to have scientific literacy as a goal or focus (not academic papers as Pella et al. had done), showed variations in the number and combinations of emphases underlying the courses examined. In comparing the aims of some courses to the course content, Roberts was somewhat skeptical of the course goals at that time, and suggested that the term “scientific literacy” may have been introduced into course
aims to give some air of acceptability to courses. He concluded: “there is some promiscuity of usage about the term” (p.19).

Many courses developed since Roberts’ analysis have continued to reflect one or other of his emphases. Fensham (1994) suggests that “(d)ifferent interest groups favour different emphases” (p. 2). Rarer has been the presence of most or all of them in the one course - there has been little effort to use Roberts’ analysis as a framework for a science course. One program which at least includes much of Roberts’ ideas, if not actually based on his categories, is Project 2061 (American Association for the Advancement of Science, 1989 & 1993) - this large American project being carried out during the late 1980s and 1990s to develop a framework which attempts to address the requirements of science literacy. (This Project is discussed more fully in section 5.3.6). The following criteria were used in that project (AAAS, 1989) to decide what content should be included, and they can be seen to cover a number of Roberts’ emphases, although not consciously drawing from Roberts:

- **Utility.** Will the proposed content - knowledge or skills - significantly enhance the graduate’s long-term employment prospects? Will it be useful in making personal decisions?

- **Social Responsibility.** Is the proposed content likely to help citizens participate intelligently in making social and political decisions on matters involving science and technology?

- **The Intrinsic Value of Knowledge.** Does the proposed content present aspects of science, mathematics, and technology that are so important in human history or so pervasive in our culture that a general education would be incomplete without them?

- **Philosophical Value.** Does the proposed content contribute to the ability of people to ponder the enduring questions of human meaning such as life and death, perception and reality, the individual good versus the collective welfare, certainty and doubt?

- **Childhood Enrichment.** Will the proposed content enhance childhood (a time of life that is important in its own right and not solely for what it may lead to in later life)? (p. xix-xx)

Perhaps the only one of Roberts’ emphases which is not clearly part of these criteria is “Self as Explainer”. The very broad base from which the hundreds of contributors to that project are drawn is significant in explaining the correspondingly broad coverage of emphases in the proposed science course. The influence of the “interest groups” to which Fensham (1994) referred, each with their own philosophy
and focus, is minimised by the sheer size of the American project in terms of the number of personnel and the areas from which they are drawn.

The Fensham (1994) publication itself is another which encourages the adoption of the full range of Roberts’ emphases in the design of a science curriculum (each of the chapters are loosely related to Roberts), although the work is actually the outcome of a series of workshops by science educators rather than an actual course document.

3.3.3 The Twelve Points Of Arons

In 1983, the journal *Daedalus* devoted an entire issue to the notion of scientific literacy. Arons (1983) listed a large number of abilities which a scientifically literate person would possess. He suggested that a list which “is neither exhaustive nor prescriptive” might be for such a person to:

1. Recognize that scientific concepts ... are invented or created by acts of human intelligence and imagination and are not tangible objects accidentally discovered.
2. Recognize that to be understood and correctly used, ... terms require careful operational definition .... and that a scientific concept involves an idea first and a name afterward.
3. Comprehend the distinction between observation and inference.
4. Distinguish between the occasional role of accidental discovery in scientific investigation and the deliberate strategy of forming and testing hypotheses.
5. Understand the meaning of the word ‘theory’ ... and to have some sense ... of how theories are formed, tested, validated and accorded provisional acceptance.
6. ...recognize when questions such as “How do we know ..? Why do we believe ..? What is the evidence for ..?” have been addressed, answered, and understood, and when something is being taken on faith.
7. Understand, .. through specific examples, the sense in which scientific concepts and theories are mutable and provisional rather than final and unalterable.
8. Comprehend the limitations inherent in scientific inquiry.
9. Develop enough basic knowledge and understanding in some area ... of interest to allow intelligent reading.
10. Be aware of ... instances in which scientific knowledge has had a direct impact on intellectual history and on one’s own view of the nature of the universe.
11. Be aware of ... specific instances of interaction between science and society.
12. Be aware of very close analogies between certain modes of thought in natural science and in other disciplines such as history, economics, sociology, and political science. (p. 92-93)

In the development of his arguments for scientific literacy throughout the rest of his article, Arons later emphasised the importance of conceptual knowledge as a pre-requisite to the attainment of scientific literacy:

To develop scientific literacy, it is essential to master at least some reasonable amount of subject matter ... (his emphasis) (p. 104-105)

He also used such contrasting terms as “operative knowledge” and “declarative knowledge” (p.94), and “genuine understanding” as distinct from “regurgitation of memorized jargon” (p.112) - in both cases stating his preference for the first-mentioned term as the ultimate objective (“declarative knowledge” was the term he used to refer to the body of so-called ‘known facts’ about the physical world, and “operative knowledge” involving an understanding of the source of and the evidentiary basis for these ‘facts’).

Arons also gave due emphasis to some aspects of practical work:

It is illusory to suppose that widespread scientific literacy will ever be successfully cultivated through instructional materials based on purely verbal inculcation. The necessary understanding, reasoning, and mastery of concepts and ideas will evolve ... only from concrete observational experience. ... Our reiterated goal … will not be attained without providing the majority of young students with hands-on experience and with sustained guidance in carrying reasoning from the concrete to the abstract. (p. 119, his emphasis)

This still does not address fully the meaning of practical work in that it only refers to observation, perhaps to form the basis of a theoretical hypothesis, without reference to manipulative and measurement skills, experimental design and practical experimentation.

3.3.4 Other Views in the Early 1980s

In the United States, the National Science Board (NSB) commissioned a report on the direction which education in mathematics, science and technology should take if America was to be the “best in the world by 1995”. Their recommendations included a call for a return to the basics (NSB, 1983a):
but the “basics” of the 21st century are not only reading, writing and arithmetic. They include communication and higher problem-solving skills, and scientific and technological literacy. (vol 1, p.v) (my emphasis)

The objectives for science education were spelled out in further detail later in the report (NSB, 1983a):

Science and technology instruction ... should be designed to produce the following outcomes:
Ability to formulate questions about nature and seek answers from observation and interpretation of natural phenomena;
Development of students’ capacities for problem-solving and critical thinking in all areas of learning;
Development of particular talents for innovative and creative thinking;
Awareness of the nature and scope of a wide variety of science- and technology-related careers open to students of varying aptitudes and interests;
The basic academic knowledge necessary for advanced study by students who are likely to pursue science professionally;
Scientific and technical knowledge needed to fulfil civic responsibilities, improve the student’s own health and life and ability to cope with an increasingly technological world;
Means for judging the worth of articles presenting scientific conclusions. (p. 44)

Despite the earlier reference to scientific literacy in the National Science Board report, the goals described above appear to refer mainly to general intellectual skills rather than to an appreciation of science in a fuller sense. They concern the ability to think, observe, question, judge and solve. These are certainly worthwhile skills, but there is no suggestion here of the need, for example, to develop an appreciation of the nature of science, or of the interrelationships between science and other institutions of society, or of the tentativeness of scientific knowledge and the method(s) by which it is produced.

One of the Working Parties within that Commission reported on K-12 curriculum for science education. Their focus for scientific literacy was explicitly directed towards the individual and had the overriding notions of empowerment and responsibility (NSB, 1983b):

Full scientific literacy involves the following four components:
Ways of knowing: What do I know? What is the evidence?
Actions/Applications: What do I infer? What are the options? Do I know how to take action?
Consequences: Do I know what would happen?
Values: Do I care? Do I value the outcome? Who does care? (p. 45)

Absent from their discussions and recommendations was any reference to the nature of science and scientific knowledge, and the human, social and cultural dimensions and role of science.

3.3.5 The National Science Teachers Association

The National Science Teachers Association (NSTA) related science literacy to the principal purpose of science education and to the then emerging science, technology and society curriculum emphasis. Yager (1996) quoted from the 1982 NSTA Position Statement:

The goal of science education during the 1980s is to develop scientifically literate individuals who understand how science, technology, and society influence one another and who are able to use their knowledge in their everyday decision-making. The scientifically literate person has a substantial knowledge base of facts, concepts, conceptual networks, and process skills which enable the individual to learn logically. This individual both appreciates the value of science and technology in society and understands their limitations. (p. 4)

There is no reason to suspect that those ideas should not extend beyond “the 1980s”. Later, the NSTA developed a 17-point listing of characteristics of a scientifically literate person. Although somewhat lengthy, the list is quoted here, in full, because it provides a valuable insight into what a detailed examination of the scientific literacy concept means, as distinct from many other discussions which tend to highlight only a few general foci of particular interest to the contributor. The NSTA (1990) considered that a scientifically literate person was one who:

a. uses concepts of science and technology and ethical values in solving everyday problems and making responsible everyday decisions in everyday life, including work and leisure;
b. engages in responsible personal and civic actions after weighing the possible consequences of alternative options;
c. defends decisions and actions using rational arguments based on evidence;
d. engages in science and technology for the excitement and the explanations they provide;
e. displays curiosity about and appreciation of the natural and human-made world;
f. applies skepticism, careful methods, logical reasoning, and creativity in investigating the observable universe;
g. values scientific research and technological problem solving;
h. locates, collects, analyzes, and evaluates sources of scientific and technological
information and uses these sources in solving problems, making decisions, and
taking actions;
i. distinguishes between scientific-technological evidence and personal opinion and
between reliable and unreliable information;
j. remains open to new evidence and the tentativeness of scientific-technological
knowledge;
k. recognizes that science and technology are human endeavours;
l. weighs the benefits and burdens of scientific and technological development;
m. recognizes the strengths and limitations of science and technology for advancing
human welfare;
n. analyzes interactions among science, technology, and society;
o. connects science and technology to the other human endeavours, for example,
history, mathematics, the arts, and the humanities;
p. considers the political, economic, moral, and ethical aspects of science and
technology as they related to personal and global issues; and
q. offers explanations of natural phenomena that may be tested for their validity.
(p.249-250)

Such a description, if taken literally, leaves one standing in awe of any
scientifically literate person should one be found, and may be an example of
the scientific literacy notion which caused Jenkins (1990) to warn that we
should not “burden (science) education with responsibilities it cannot hope to
meet” (p.49). But the list can also be considered as demonstrating the overall
spirit or focus of any science education course, if the general picture rather
than the detailed brush-strokes of the NSTA description is accepted.

3.3.6 Project 2061

Reference has already been made to the work of the American Association
for the Advancement of Science (AAAS). In 1989 the AAAS published their first
Project 2061 report entitled Science For All Americans, and offered the following
“broad definition” (AAAS, 1989) of scientific literacy, each aspect of which can be
found within the list of characteristics described by Arons earlier in this section:

Scientific literacy - which encompasses mathematics and technology as well as the
natural and social sciences - has many facets. These include being familiar with the
natural world and respecting its unity; being aware of some of the important ways
in which mathematics, technology and the sciences depend on one another;
understanding some of the key concepts and principles of science; having a capacity for scientific ways of thinking; knowing that science, mathematics and technology are human enterprises, and knowing what that implies about their strengths and limitations; and being able to use scientific knowledge and ways of thinking for personal and social purposes. (p. 20)

Despite the AAAS’s acknowledgment that it was providing a broad definition of scientific literacy, their *Project 2061* outline does not appear as liberal as that of Arons with his greater emphasis on the processes and nature of science. The American project does, however, give further insight into its understanding of scientific literacy in its chapters describing details of the focus of a new curriculum direction. For example, the introduction to the chapter on “The Nature of Science” in AAAS (1989) sets the following scene:

Over the course of human history, people have developed many interconnected and validated ideas about the physical, biological, psychological, and social worlds. These ideas have enabled successive generations to achieve an increasingly comprehensive and reliable understanding of the human species and its environment. The means used to develop these ideas are particular ways of observing, thinking, experimenting, and validating. These ways represent a fundamental aspect of the nature of science and reflect how science tends to differ from other modes of knowing.

It is the union of science, mathematics, and technology that forms the scientific endeavour and that makes it so successful. Although each of these human enterprises has a character and history of its own, each is dependent on and reinforces the others. (p. 25)

This begins to show a richer interpretation of scientific literacy within the *Project 2061* proposals. The second publication associated with the project, *Benchmarks for Scientific Literacy*, (AAAS, 1993) provided even more detail, indicating the expected stages of student development and understanding, at different levels of their schooling, for all aspects of science education. The areas which are seen as important form the basis of the main chapter headings and at least six of the twelve (see emphasis) relate to the nature of science/mathematics/ technology, to the human and historical underpinnings, or to overviews of the scientific process:

The detailed exposition of the stated goal of science education gives a clearer picture of the meaning of the scientific literacy term than a definition formally given within one paragraph. This points to a significant difference between the work produced by the AAAS and the journal-based contributions of many others - the former provides, in full detail, the description of a complete science program for primary and secondary schooling. In doing that, the AAAS was able to indicate much more clearly its view of the meaning of the term “scientific literacy”. As Jenkins (1995) explained:

Benchmarks is about the construction of curricula against an operational definition of “scientific literacy” ... (p. 448)

3.3.7 Other Views in the Later 1980s

At about the same time as Science For All Americans was published, Shortland (1989) was contributing to the debate on scientific literacy and the public understanding of science in England. He suggested that the former term “is a more appropriate goal” (p.306). In drawing on work done by a Project Team which he coordinated (see Thomas & Durant, 1987), Shortland summarised several arguments which have been put forward by different groups in support of a public understanding of science. In addition, he proposed that two additional notions associated with scientific literacy - one based on an “individual” argument, and the other on a “political” argument - could more powerfully “articulate and give expression to lay people’s desires, aims and ambitions with respect to science and technology in today’s world” (p.312). With respect to the individual, he reasoned that “more knowledgeable citizens ... are able to negotiate their way through the society in which they live” (p.312). Specific examples referred to issues associated with diets, health care, safety and consumerism. His political emphasis for scientific literacy related the need for people in a democratic society to have some understanding about science if they are to participate constructively in decision-making on science-related issues. In addition to these philosophical emphases for scientific literacy, Shortland (1989), like Arons, described a set of criteria which he considered should be used to characterise the notion:

1. An appreciation of the nature and aims of science and technology, including their historical origins and the epistemological and practical values which they embody.
2. A knowledge of the way in which science and technology actually work, including the funding of research, the conventions of scientific practice, and the application of new discoveries.

3. A basic grasp of how to interpret numerical data, especially relating to probability and statistics.

4. A general grounding in selected areas of science ...

5. An appreciation of the inter-relationships between science, technology and society, including the role of the scientists as experts in society, and the structure of the relevant political decision-making process.

6. An ability to update and acquire new scientific knowledge in the future. (p. 314-315)

Arons’ outline of scientific literacy contrasts with that of Shortland in that the former has an epistemological theme whereas the latter clearly reflects the “individual” and “political” dimensions which he emphasised. Despite this, there are still similarities between the two descriptions. In particular, Arons made reference to the essentially human character of science, the modes of scientific discovery, the mutability of scientific theories and the influence which scientific knowledge has had on intellectual history. All of these could be considered to be implied by Shortland’s first component. Arons referred to the developing of knowledge and understanding of some scientific theories, as did Shortland. Arons also suggested that a scientifically literate person would have an awareness of the interactions which exist between science and society - Shortland did likewise. Additional features of the Shortland list were the specific reference to an appreciation of the mathematical aspects of interpretation of results of scientific inquiry, and the requirement of a continuing interest in new science (although this latter is similar to the ability to read science-related material intelligently and to learn without formal instruction which was espoused by Arons).

Another to have expressed opinions about scientific literacy is Shahn (1988). Although she did not enumerate a set of goals in as much detail as Arons did (few others have done so), she suggested

[that] the science-literate person must have both a cognitive level that supports reasoning skills, and language skills that permit making and expressing distinctions

and further,
that [an] appreciation of the process of science can be enhanced by studying the
development of critical concepts in an historical context rather than emphasizing
current beliefs (p.42).

Her opinion was that the teaching of formal scientific reasoning without
reference to what often happens in science was providing the basis for student
misconceptions of what science is really like. “The history of science abounds with
what we now see as “wrong” conclusions” (p.44). Reasoning to produce a “correct”
conclusion presupposes that all relevant information is at one’s disposal and that there
are no external cultural or societal influences on the reasoning process; those
presuppositions have clearly not always been the case throughout the history of
science.

3.3.8 Scientific Literacy in the 1990s

Jenkins (for example, 1990, 1992, 1994 and 1995) has made a number of
contributions to discussions about scientific literacy (and the public understanding of
science, which will be discussed in section 3.4.2). Not only has he referred to a
number of recent studies and contributions on scientific literacy, but he has also
drawn attention to the reasons which have been proposed for the adoption of a
scientific literacy emphasis in schools, the extent to which we can expect to achieve
scientific literacy, and the limitations which should be placed on its definition if its
goals are to be achievable. Within the context of the discussion in this chapter on
meanings, he has had less to say regarding definitions, in terms of his own preferred
model. Accordingly, detailed analysis of Jenkins’ ideas will not be summarised here,
but this is not to reduce the significance of his contributions - they provide a
commentary on the viewpoints referred to and summarised in this chapter on such
meanings and models as have been proposed by others.

Of the authors thus far referred to in this chapter, some have summarised and
analysed the works of others, while others have proposed their own view of scientific
literacy. Another group to examine the contributions of others are Atkin and Helms
(1993) who viewed the scientific literacy term as coming after the many statements
which have been made of the aims for science education:

These days the collection of desirable aims is often summarized as fostering
scientific “literacy”. And it is intended to be for “all” students. Neither of these
The approach implied here (aims which are recognisable and able to be implemented at the classroom level) is a more productive one for science education than attempting to define a term. After all, the essential requirement is to have a set of goals and emphases on which to base a science curriculum - if a particular term is seen as being a useful umbrella name for the aims outlined then so be it. Some problems and confusion have arisen on account of the same term being used by people with different ideas about what science education should be trying to achieve. Atkin and Helms lamented the lack of debate about goals, as distinct from propositions of goals themselves. That is, their view was that much of what was being published did not involve interaction between contributors - rather they considered that statements were made by some in comparative isolation to the work of others. In attempting to find common ground between a range of reports, they suggested that there was “unmistakable consensus about several aspects of science education”. Five in particular are described:

- Major concepts of science should be stressed.
- Breadth of coverage should be replaced by studies in greater depth.
- Multi-disciplinary and inter-disciplinary approaches are becoming more prominent features of science; to an increasing degree, cross-disciplinary themes also characterize the field.
- Science necessitates active investigation by the student and clear communication about processes and results.
- Complex levels of analysis and problem-solving characterize science. (p. 3)

While noting that there are other less-commonly-agreed-to directions for science education, Atkin and Helms recognised three further ideas which were attracting “earnest and increased attention”:

- Science is a product of human thought and action. That fact suggests an emphasis on the intellectual and social history of the subject as a way to understand and appreciate how people generate, test, and use ideas. Emphasis in the curriculum should be placed on justification for scientific ideas ... and the influences and processes by which they are accepted or rejected. Those influences should include forces both internal to science and external.
- Practical reasoning, like scientific reasoning, is a prominent characteristic of human thought and action ...

- Certain “habits of mind” are among the most important outcomes of science education. (p. 3)

Atkin and Helms further argued that debate on goals should include opinions on priorities among those goals. Accordingly, they proposed that these latter three be accorded a privileged position above the first five; that is, they belong in the foreground as central goals for science education. … [They] relate more directly to an appreciation of science, mathematics, and technology by the average citizen … [who is] concerned about economic productivity, about the relationship of science to their personal lives, and about the need to make responsible decisions … [and] they have greater inherent interest for the average student. (p.4).

More recently still, and of significance for Australian science education particularly, was the study undertaken by Goodrum, Hackling and Rennie (2001) whose report included an overview of the scientific literacy concept during the previous two decades. They referred to other works (such as Bybee, 1997) for more thorough discussion on the meanings of scientific literacy as well as providing their own explanation of the term. While recognizing the difficulty in offering a short definition, they suggested that three areas should be focused on:

the content and concepts of science, … the nature and processes of science, … and the relationships between science and society. (p. 14)

Further on, they referred to interest in and understanding of the world around us, an ability to engage in discussions about science, a willingness to be constructively critical of scientific claims, an ability to draw conclusions based on evidence, and a capacity for informed decision-making as capabilities which increase a person’s scientific literacy.

3.4 Other Science Curriculum Emphases

While the focus of this discussion has surrounded the notion of scientific literacy, it is worth noting that the term tends to be used to draw together a range of other more specific movements such as “Science For All”, the “Public Understanding of Science”, “Social Responsibility in Science”, and the “Science, Technology and Society” movement. Accordingly, these are examined briefly here to see what they have to offer in painting a picture of scientific literacy.
3.4.1 The “Science For All” Concept

Atkin and Helms (1993) referred to desirable aims for science education and to the intention that the goal of science literacy should be for all students. This was a reference to one of the other phrases - *Science For All* - commonly used in relation to recent calls for reform in science education. An early reference to the use of the term is uncovered by Uzzell (1978) who traced the changes in emphasis in English science teaching since the mid nineteenth century. He called attention to “(t)he publication in 1916 of Science for All by a group of public school science masters”, commenting on “its (considerable) influence on later thinking” (p.13). *Science for All* also appeared in the title of the first of the *Project 2061* publications. Its underlying philosophy was that science education (at least up to the first 10 or 11 years of schooling) should be directed away from the types of courses which, in effect, were intended to provide an appropriate background for those who were potential students in tertiary science courses. As this was only a small percentage of students it was argued that there were large numbers of students doing work which they were not suited to, had no interest in, and which provided them with little benefit. The Science For All movement argued that science courses should be developed which had meaning and value for students who not only might be going on to tertiary courses, but also for those who might move into technical courses, take up apprenticeships, begin careers which may not have any connection with “academic science”, for those who may experience learning difficulties, for those in other “minority” groups, and for many girls. Although the 1960s and 1970s produced changes in science courses, they were essentially changes in the way the science message should be taught, rather than changes in the message itself. Fensham (1985) made this point when he said:

> the science curriculum projects of the ‘60s and ‘70s did set out to extend science as it was known in the curriculum elite secondary schooling to a much wider cross-section of school learners. In other words, the content and topics of these elite science curricula were taken as the knowledge of science that was worth learning more generally, and the projects directed their energies to devising new presentations and forms of pedagogy which it was hoped would achieve this goal of more and more learners acquiring this knowledge. (p. 427)

Like Scientific Literacy, the meaning of the *Science For All* phrase also adopted a new focus during the early 80s, having been revived in the late 70s. Both notions had been employed in earlier years and were recalled into common usage.
about the same time. Given the overlap in their range of meanings, as will be discussed below, it is likely that the different terms represented two sides of the same coin: the recognition of a need to reconsider the basic principles and goals of science education.

Recent use of this term originates from the 1970s in a lecture by James Callaghan in Oxford. Hodson and Reid (1988a) also referred to a document produced by the Department of Science and Education in England in 1977 and which proposed the notion of a “(s)cience education for all” (p.3). In this, it was suggested that everyone has

a right to understand and to become involved in problem-solving processes which they will face in day-to-day living and which require the knowledge and disciplines of science. (Hodson & Reid, 1987, p.3)

Since then, the definition of Science For All has been expressed in much more detail. Blin-Stoyle (1984) said it should contain “studies of science, its applications and its social implications, (and) some technology”. Fensham (1985) gave a most detailed description of Science for All, suggesting that it include content which is of immediate, personal and social benefit to students, has attainable (for students) criteria, has clearly evident themes, incorporates practical activities, enables cognitive skills to develop naturally from a study of various topics, and recognises that students begin their science studies with some unconsciously-structured framework of science already in place. He provided a non-exhaustive list of ten aspects of a science curriculum:

Knowledge ... Applications of knowledge ... (intellectual) Skills ... Practical skills ...
Problem-solving ... Science traits and attitudes ... Applications of science and technology ... Personal and social needs ... The evolution of scientific knowledge ... Boundaries and limitations of science. (p. 426-427)

The Science for All concept is primarily aimed at students aged up to about sixteen, that is, until just before the last two years of senior secondary education, as it is in many countries. Fensham (1985) was of the opinion that two separate streams of science education were called for beyond that level, and that traditional formal science should not occur below that level, even for a specialised group of students. He proposed a containment policy to restrict the “elite or traditional education in the sciences ... to (and not allowed to occur below) some agreed upper level of
At this higher secondary level, Fensham envisaged parallel streams of students studying different types of science: the “Science” stream taking some or all of Physics, Chemistry and Biology, and the “Humanities” stream studying Physical Science. Ziman (1980) advocated a similar structure in which he conceded that, for A level and beyond, there was a need to focus on “valid science” and “the real need (at this level) is for distinct courses of study specifically directed towards (non-science-specialist) themes” (p.142). This contrasts with the scientific literacy imperative which generally takes the end of secondary schooling as its timeframe and does not distinguish between different directions in student academic interest. More importantly, it ensures that those who will eventually be scientists will be taken away from any further opportunity to appreciate, at a higher level, those things - such as the nature and limitations of scientific knowledge and science, and its relationship with society -which are essential for scientists to be aware of, if they are to adopt the ethics and carry out the responsibilities of their positions. Cross and Price (1992) express similar concerns about Ziman’s view in this regard:

There is an urgent need for a new generation of scientists and technologists who have a better understanding of the nature of Science, who can understand it in its social context. If they are not trained differently the much-needed reform of Science may not occur. In addition to the concepts and skills of traditional science courses the kind of teaching we are advocating will introduce that interest in, and concern for, relating science to the wider community which is so essential today for specialist and lay-person alike. (p.102)

Comparisons can be made between Fensham’s list of directions to be taken by science courses under the banner of Science For All and the list proposed by Arons (1983) and described here in section 3.3. There is almost complete correspondence between the two, especially if account is taken of Arons’ emphasis, made elsewhere in his article, on the understanding of content and the carrying out of practical work. Contributions from others (for example, Hodson & Reid (1988a) & (1988b)) show similar correspondence.

3.4.2 The “Public Understanding of Science” Concept

As the title suggests, it is the general population who are the focus of this concept, although there is a recognition that its goals can be addressed at least in part by secondary education. Although there had been investigative research into what the public knows about scientific matters prior to 1985, it was the monograph published
by The Royal Society (1985) which drew attention to the issue, and which resulted in the phrase having the status of a slogan or “universal rallying call” (the term by which Hodson and Reid, 1988a, described the Science for All notion). Among the groups which The Royal Society saw as having some responsibility in providing a better public understanding of science were the education system, the parliament and its scientific committees, the media, industry, scientists, and The Royal Society itself. They considered five different groups as comprising the public: private individuals (using science “for personal satisfaction and wellbeing”, p.7), individual citizens (“for participating in civic responsibilities”, p.7), those in science or technology-oriented occupations, those in middle-management areas of employment, and those responsible for making large-scale decisions affecting society (that is, primarily those in industry and government).

In achieving a greater understanding of science among the wider community, The Royal Society (1985) set out aims for formal science education. They included:

- (i) to develop the processes of scientific thinking .... observing, pattern-seeking, explaining, experimenting, communicating, applying;
- (ii) to acquire a range of mental and manual skills through direct involvement in scientific activities;
- (iii) to acquire some knowledge and understanding ... of the body of knowledge called “science”;
- (iv) to understand the nature of an advanced technological society, the interaction between science and society, and the contribution science has made, and can make, to the cultural heritage. (p. 17)

The Society proposed a “balanced education in science for all to the age of 16” which should involve:

- the main three traditional disciplines in science and others (such as Earth sciences), the connections between them, and with many examples drawn from everyday life,
- not only scientific knowledge but also scientific method, the nature and limitations of science, history of science, and the connections between society, science and technology,
- the problem-solving characteristics of science and technology which bear on issues of economic, aesthetic or social importance,
• the value and use of mathematics in assisting to model various phenomena, and
• the use of statistics to interpret, explain and predict (p. 17)

Yet again, the same themes can be seen as those listed earlier in the rhetoric of both the Scientific Literacy and the Science For All groups. In particular, comparisons can again be made with the outline proposed by Arons for scientific literacy, and very close agreement is evident, except perhaps for Arons’ lack of specific reference to the application of mathematics as part of his conception of scientific literacy. As in previous listings of one or other of the sets of goals for science education, a number of the key features necessitate some awareness of episodes and themes throughout the history of science. The fourth point of the aims set out by The Royal Society requires some awareness of the history of science - the only way to understand the relationships between science, technology and society is to study them in episodes from the recent or more distant past. Similarly, the contributions which science has made to a society’s cultural heritage refers to the actual examples in history wherein such interrelationships have occurred. In their description of a suggested course content for science education, the Society explicitly includes the history of science, and the nature and limitations of science as being one of the five areas which it sees as important in its ‘balanced’ science education.

The use of the rhetoric of the public understanding of science is not limited to The Royal Society. Layton, Jenkins, Macgill and Davey (1993) regarded it as being of paramount importance:

The public understanding of science is a matter of concern in most countries. (It) is commonly regarded as essential for the effective implementation of a wide range of social, economic, technological, medical, employment or other policies which have a scientific dimension. (introductory page)

3.4.3 The “Social Responsibility in Science” View

Ramsey (1993) used the term “civic literacy” as the dimension of scientific literacy which indicated the intent of “social responsibility”. The phrase “meaningful participation” suggested the observable goal of science education. He directly linked the notions of social responsibility and scientific literacy:

... social responsibility has an established life space in the scientific literacy literature. (p.237)
In further clarifying his position, he suggested that social responsibility is the “behavioural dimension” of scientific literacy.

Cross and Price (1992) gave a greater importance to the term when they said that it involved “an understanding of the social influences which shape the Science and the full range of consequences which follow from it” (p. 2), and the “moral accountability of Science as an institution to the wider society”. Specifically in relation to education, they said:

... the special responsibility of Science teachers [is] both teaching in a way that reveals the socially produced nature of Scientific theory and teaching the Scientific knowledge and skills required for an understanding of the social issues which the public is increasingly being faced with. (p. 2)

In relation to the latter aspect, they presented a new definition of that notion, contrasting it with the long-held view:

Teaching the Scientific knowledge and skills required for an understanding of social issues ... requires a different attitude to Science from that which has been traditionally held by classroom teachers. Discussion of Scientific evidence involves more than concepts and skills. It requires consciousness of the nature and role of theory in the scientific process and understanding that Science is produced (constructed), rather than discovered. (p. 2)

3.4.4 The Science, Technology, and Society Movement

The last of the recent reform movements to be discussed in this chapter and which suggest reform in science education approaches is the Science, Technology, and Society movement (referred to hereafter and commonly elsewhere as STS). It too can be shown to have features in common with scientific literacy, and to have historical imperatives. Layton (1994), in his review of the Cross and Price text, drew a link between the social responsibility and STS movements by regarding the former as the “theoretical core” and the latter as the “conceptual framework”.

Ziman (1980) is regarded as a seminal work in the development of the school STS movement. In that work he listed a number of titles signifying similar approaches to science education - names such as Social Studies in Science, Science of Science, Science and Society, and many others. He suggested that the collection of such courses be called “cryptically, STS, short for Science, Technology, and Society”
His stated purpose of STS education referred to the more traditional view of science:

The principal defect of conventional science education is that it gives a very one-sided impression of science and technology. The fundamental objective of STS education is to correct this impression by teaching about science in its social context. By this means it is hoped to broaden the background of students of science and technology, and to prepare them better for their lives as professional workers and responsible citizens. (p. 108)

Later on, Ziman emphasised the same point:

The main thrust of the STS movement is to oppose scientism and technocracy; it must reject any similar narrow formula that pretends to know all the answers to all the problems of our times. (p. 111)

And yet again, in reference to conventional courses, even those which incorporate everyday contexts as part of the development of theoretical principles, he suggested:

(They miss) altogether the personal and social dimensions of basic science and technological research. There seems no call to stop and look at the scientists themselves .... The whole question of the place of science in modern culture has already been answered by implication - in typical technocratic terms. .... In other words, this [traditional] approach can scarcely avoid a heavily scientistic bias, where scientific “validity” and technical “capability” always remain dominant over needs, and values, and satisfactions, and ultimate goals. (p. 103)

Fifteen years later, Yager and Lutz (1995) were making similar points about the foundation upon which the STS movement is built. They referred to the "ubiquitous problems in school science" as relating to textbook dependence, higher education prerequisites, lack of personal relevance, teacher authoritativeness, knowledge as superior to comprehension and application, and narrowness of vision. Like Ziman, they pointed to the standard approach to school science and the need to develop a curriculum approach which did not suffer from the shortcomings of the former:

Traditional structures have reflected misconceptions about what the nature of science really is. There is a perceived need for something radically different from the conceptual schemes (discipline structures) used by practicing scientists. ... STS is the teaching and learning of science in the context of human experience, including the technological applications of science. .... Science teaching via an STS
strategy begins with a societal context and includes a consideration of technology.

(p. 30)

Relating the STS concept to the over-riding notion of scientific literacy as it is presented in this thesis, Yager (1992) argued that “STS provides direction for achieving scientific and technological literacy” (p.3). According to Yager (1996), it required “personal, societal and career imperatives (being used as) organizers for the curriculum” in STS courses (p. 9). In this sense, STS approaches are those which develop their science out of an examination of societal issues which have scientific principles as a significant component. The plural (‘approaches’) is used here as there is no single, defined classroom methodology for STS - “(t)here remain conflicts as to what it is and what it is not” (Yager (1996)). Along the way, students come to see science as part of a larger integrated picture which clarifies the relationship which they have or can have with the society of which they are a part. They are also able to see more clearly and accurately what science is by “doing science”, in the most general sense of the term. Yager (1996) argued that this approach is essential in demonstrating the utility of concepts and processes, and ultimately in achieving scientific literacy. The traditional approach of first tackling the often-abstract concepts runs the risk of losing students before they can appreciate the utility of science - on both counts resulting in the charge of scientific illiteracy by observers of students’ ability.

Cross (1990) advocated caution in the adoption of the STS “issues” approach if it did not incorporate social responsibility as an integral part of its philosophy. A possibly dangerous situation could result from the unquestioning acceptance of the positive value of technology if his warning is not heeded.

Others to have contributed significantly to the STS debate in school curriculum include Aikenhead, in Canada, and Solomon, in England. Bennet (1995) discussed in detail the views of each of these. Both educators recognised the importance of producing an informed citizenry (with respect to science-related issues), and in relating scientific knowledge and concepts to everyday situations.

While there is no single, carefully-described curriculum which defines STS, Ziman (1980) recognised a number of approaches which might be successfully employed. One of these enables this discussion to return to its central theme:
The STS movement favours an historical approach ... to demonstrate science as the epitome of the spirit of change. (p. 119)

While accepting the drawbacks and difficulties associated with this and other approaches, he suggested that history is at least one of the worthwhile ways in which an STS can be constructed. One of the problems with STS itself is the Feyerabendian freedom which it allows in its implementation. This makes it difficult to argue for or against any of its principles, or to draw firm conclusions from them, particularly with respect to the historical theme which is the basis of this thesis. In as much as STS is regarded as a means to scientific literacy and it promotes a strong human character to the study of science, a historical approach to science education is seen to be important in an STS curriculum.

3.5 **Feminism and Science Education**

There are two aspects to the feminism issue in science education. One relates to particular views of nature and of science, to approaches to doing science, and to the contributions of women in science. The other dimension addresses methods by which a gender imbalance in senior secondary school science classes may be reversed. While notions of gender are often separated from those of feminism, there may be a connection between the two if it is thought that feminist science may be of assistance in redressing the gender imbalance by making science more attractive. Both ideas are raised here to illustrate how they relate to some of the characteristics of scientific literacy, in particular to those which allude to the need for an historical approach to science education.

To the extent that feminist science proposes an alternative view of science it is a legitimate area of study within the scientific literacy theme - present-day conceptions include reference to an appreciation of the nature of science. Inter alia, the nature of science involves an examination and understanding of the way nature is viewed and interpreted. This necessarily requires an appreciation of the existence of different views, each of which has developed within a particular social milieu. Specifically, the widely-recognised mechanistic world view, which was the basis of the work of Descartes, Newton and others and which has dominated western society’s view of nature since then, is not universally accepted as the only view. Although it is not the purpose of this thesis to elaborate on the details of such other views, it is sufficient to refer to Capra (1982), for example, to see the explanations of the
“bootstrap” approach in particle physics, or the “systems view” as a basis for explanation of the characteristics of living organisms, or the “holistic” approach to health, or the “organic” world view which dominated world thinking prior to 1500. Merchant (1980) developed this latter theme as a view of “nature as female”. Longino (1990), like Capra, also examined “wholism”. Many of these views are collectively referred to as “feminist” perhaps because they incorporate attitudes which have traditionally been regarded as relating to female characteristics or qualities. Longino explained it as follows:

Such a science is said to be feminist because it is the expression and valorization of a female sensibility or cognitive temperament. (p. 187)

Some of these approaches are alternative proposals for a present-day view of the world, others are descriptions of past paradigms. In gaining an appreciation of the nature of science it is important to see how it is developed within the extant paradigmatic world views. To the extent that some of these have been labelled “feminist”, an appreciation of the nature of science incorporates a study of feminist science.

Harding recognised the importance of historical studies to highlight the contributions which women have made to science and the factors which bear on how those contributions were made possible in what was largely an androcentric academic climate. She was careful to acknowledge the work not only of outstanding women but also of the majority who do not achieve the lofty heights of the few. In this, Harding (1991) saw the situation as no different from men, in terms of the atypical nature of the contributions made by those “great” men and women at the cutting edge:

Someone intending to teach or write about women’s situation in science by generating from these women’s lives would do a great disservice to the rest of the women in the sciences. This is especially true if the history of the great women is reconstructed uncritically from such conventional historical sources as, for instance, Watson’s account of Franklin. But it is also true if the history is reconstructed from the women’s own accounts. They, like the rest of us, have been woefully unaware of the larger forces outside their immediate environment which have tended to shape their opportunities. Also, they have sometimes been unaware of the meanings that their achievements and their lives have had for other women. ... Women’s contributions to the history and practice of science are not limited to the achievements of a few extraordinary individuals. The new women’s history and sociology have directed attention to the less public, less official, less visible, and
less dramatic aspects of science in order to gain a better understanding of women’s participation in these enterprises. (pp. 25-26)

The issue of gender imbalance in science education is separate from feminist science, but opinions have been expressed suggesting that an education which recognises the latter may assist the former. Harding (1991) argued that such an approach would not be purely to enable girls to assimilate more easily into traditional science (as education or career) but would be of benefit to boys also. She went further than talking of different approaches to science education; she wrote of the need for new approaches to science itself to “close the gender gap in scientific and technological literacy … (but that these) new sciences are not to be only for women” (p.5, her emphasis). She decried many aspects of traditional science:

conventional scientific education available to boys is woefully flawed in that it is structured by unrealistic and politically damaging images of and goals for scientific activity. (p. 31)

Harding’s science education is similar to the approach outlined in the earlier section on Social Responsibility (section 3.4.3). She too focused on the societal issues (“medical treatment, …computers, … telephones, … Agent Orange, … Dalkon shields, … polluted air and vast oil spills, …”, p.2) and the need for responsibility in the development and use of science and technology in society.

Kahle (1985) drew on numerous research studies which highlighted either the under-representation or under-achievement of girls and women in science education and science-related careers. Efforts which attempt to redress these imbalances should include “new approaches to teaching science [which] must present its egalitarian image” (p. 225). This egalitarianism with respect to masculinity and femininity in science requires a study of and an exposure to a range of people who have been involved in and contributed to the developing of science. For example, Kahle (1985) suggested that “Barbara McClintock’s work should be included in every chapter concerning genetics” (p. 214). In general, however, Kahle’s discussion of successful approaches and innovations which addressed the gender issues in science education were essentially set within the framework of the traditional science curriculum. Harding’s suggestions (see above) take that extra step by considering an approach which is unrestrained by the philosophy of standard science education.
In contrast, Matthews (1994) was reluctant to accept feminist views of science as legitimate and argued that feminist science is not what is required to increase girls’ participation and performance in science. Nevertheless, he was emphatic that, at least for teachers if not for students, the “weighing up of (the) arguments” requires an understanding of the history of science:

Feminist critiques of science ... are other areas where knowledge of the history and philosophy of science is important. (p.108)

And further,

weighing up these arguments ... is impossible without the knowledge of the history and philosophy of science. (p.108)

In either case, feminist science is inextricably linked to those characteristics of scientific literacy which refer to the nature of science and to the people who have shaped science, and hence also linked to a historical approach to science teaching.

3.6 **Difficulties with the Scientific Literacy Notion**

There have been views expressed suggesting that scientific literacy is either not achievable or not necessary, and such views may cast doubt on whether the concept should be retained as a directing influence on curriculum. Such arguments fall into at least three categories:

1) the difficulty of achieving any degree of competence in making scientific judgements. Shamos (1988) considered that “no reasonable amount of scientific training could possibly prepare one to form credible judgements on the wide variety of issues the country faces. ... [e]ven professional scientists frequently disagree on science-based public policy issues” (p. 20), this line of argument being based on the assumption that scientific literacy is a “guarantee of certainty” (p. 20);

2) in ‘real’ situations, the resolution of issues is ultimately based on non-scientific grounds. Thomas and Durant (1987) were of the opinion that “in the end the problem will only be overcome by resolving issues that are fundamentally moral and political” (p. 10);

3) society has survived satisfactorily so far without any great degree of scientific literacy. Again, Shamos (1988) pointed out that “widespread scientific literacy is not essential to develop an intelligent electorate ...
or to prepare people for life in an increasingly technological society” (p.16, his emphasis). This is not so much an opinion as a conclusion, based on low levels of scientific literacy among the general population and the assumption that we nevertheless have an “intelligent electorate”.

Those who have proposed such arguments are not necessarily completely against all attempts to work towards scientific literacy. They generally see other more important advantages in the concept. Ultimately, any arguments proposed against scientific literacy on the grounds that it is “too difficult” or “not necessary” can be answered in terms of “freedom of information” or “avoidance of scientism”. Thomas and Durant (1987) suggested that “the task ... should be to ensure that science is at least as publicly available and accessible as are other major products of human creativity” (p. 12). They also drew on A. Hunter Dupree’s view, expressed in the journal *Science* in 1961, which

warned that the isolation of science from the rest of American culture was producing a scientific “cargo cult”. ... Failing to understand science properly, the public responded with a mixture of fear and adulation. (p. 6).

Shamos (1988) remained negative towards what he saw as the means to achieve scientific literacy. He pointed to the increasing alienation which students experience towards science as they study it throughout school. It may be that science courses at that time were not truly designed with a liberal scientific literacy as their basis. He suggested the adoption of the “less ambitious” goal of encouraging an “appreciation of science and thereby (keeping) open the possibility of full literacy for some individuals” (p.20, his emphasis). This affective goal of an “appreciation of science” may well be the outcome of courses designed along the lines of Arons’ scientific literacy characteristics.

Thus, although there may have been, and still are, doubts expressed about some of the arguments which are proposed in favour of scientific literacy or about its fundamental achievability, any conclusion which implies that the goal should therefore be dropped is untenable.
3.7 **Conclusion**

This chapter began with an examination of the conceptions of scientific literacy which have been explicitly or implicitly held during the years since the early 1950s. A more detailed investigation was undertaken of the recent (since the early 1980s) conception of the term. In particular, the ideas proposed by Arons (1983) were used as a reference point for the discussion and common features were noted between his description of the concept and those put forward by others. There are a number of science education movements which have arisen since the early 1980s and the links between each of these and the concept of scientific literacy were examined.

Lastly, some reference was made to feminism. Some of the connections between that movement, science and science education were indicated, particularly those which had implications for any of the criteria for scientific literacy.

It is not the purpose of this research to add to the range of definitions of the term by proposing further interpretations of the concept, but rather to examine what it has meant to many science education researchers. A key theme running through many of their opinions has been the ‘nature of science’ as one of the components of their description of scientific literacy. Arons’ contribution to the debate provided the greatest detail in describing what might be regarded as the characteristics of science, and at least some of these were invariably present in each of the subsequent explanations of the scientific literacy notion described throughout the rest of the chapter.

Irrespective of what might form a complete definition of scientific literacy, it is clear that there is widespread, if not universal, agreement with the necessity of an appreciation of the nature of science as a key component. Accordingly, the following chapter examines in more detail what the nature of science might encompass so that the path to the attainment of scientific literacy may be made clearer.

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CHAPTER

4

THE NATURE OF SCIENCE

4.1 Introduction

This chapter focuses on what needs to be understood about science, in addition to the conceptual content which is common to traditional courses at the senior secondary school level. These additional features of science include such varied aspects as the nature of scientific knowledge, the differing roles played by theories and laws, ways in which theories can and do change, the processes of scientific knowledge production, the role of experimentation and the way that role has changed over time, the significance and difficulties associated with replication of experiments, the theory-laden nature of observations, the meanings of discovery, the importance of communication in the development of scientific knowledge, and the interrelationship between and the mutual interdependence of science and other societal institutions especially technology. Some of these features are discussed from a sociological standpoint, while others are more appropriate to the realm of philosophy of science.

As indicated in Chapter 1, it is not the purpose of this thesis to produce a comprehensive study of the sociology or philosophy of science. It is important, however, for science educators and their students to have some understanding of the ways in which the processes and operating principles of the scientific enterprise may be described and explained. Nor is it the intention to suggest one particular view of sociology or philosophy of science. What is important is to recognise that the processes of science contribute to the form of the scientific knowledge produced and so are worthy of study; different approaches to the study of the same phenomenon may produce different knowledge. This study is carried out with the view to addressing the aims of a science education curriculum which take into account the modern conceptions of scientific literacy as described in Chapter 3. Discussions of the nature of science in the literature, some of which forms the basis of study in this chapter, are generally wide-ranging to reflect the multi-faceted characteristics of science. However there have been very few attempts to arrange such characteristics into a complete framework, despite the value which such a framework would have for
The ‘Nature of Science’ has rarely been a formal component of secondary school science curricula. Jenkins (1996) noted the difficulties associated with many attempts to do so. Secondary science curricula are always described in detail and mandated by an authority beyond the individual school level for the senior years, but not necessarily with such precision or compulsion at lower levels. Consequently the clearest indication of the incorporation of any study of the Nature of Science in science programs can be obtained by examining course outlines at these senior levels. A typical example of such a science course is that of the physics Study Design for Years 11 and 12 of the Victorian Certificate of Education (Board of Studies, 1999). Other examples can be found in the syllabus outlines of any other State education department such as the one published by the Senior Secondary Assessment Board of South Australia (1999) for Physics. The Victorian course prescribed the teaching of a range of concepts including topics such as electromagnetism, motion, electronics, sound, and light & matter. In the introduction section of the Study Design by the Board of Studies the aims of the course are stated to include ideas such as “ways in which knowledge is developed”, and “physics as a particular way of knowing” (p. 7). However, throughout the detailed course description within the Study Design, there is virtually no reference to the construction of knowledge, epistemology or the value and importance of understanding what science is. The South Australian course outline is similarly focused on concept development with no reference even in its Rationale to the nature of science or related concepts. The focus is squarely on an understanding of the “small number of fundamental laws [which] can explain an enormous range of phenomena” (p. 1). Wilkinson (1999) found that textbooks generally make scant reference to such ideas and the formal examinations in the subject only focus on conceptual knowledge of physics.

The absence of any attempt to explicitly address those wider issues will result in students forming a view of the nature of science nevertheless. The ways in which science is presented in texts, by the teacher and by curriculum designers all contribute to the view of science which students come to form. Such views have been reported
by authors such as Lederman (1992), Griffiths and Barry (1993), Lucas and Roth (1995), and Tobin and McRobbie (1997).

A more explicit picture of science can and should be presented, one based on a greater awareness of how scientific knowledge evolves. When it is recognised that science is a product of people’s thoughts, interpretations and interactions with their environment, there is much that can be examined and analysed about the way scientific knowledge is produced. If all that is communicated to students about science are its ‘laws’ and ‘theories’, which are often portrayed as dictating the way nature behaves rather than explaining or describing it, students only encounter the conclusions of science, and not its processes. Schwab (1964) referred to

> [the] unmitigated rhetoric of conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths. (p. 24)

Apart from any other difficulties this presents, at the very least it leads to a misunderstanding of the limitations of the applicability and fallibility of those ‘laws’ and ‘theories’.

The development of a clearer understanding of science and its processes needs to be incorporated into science education programs at the secondary school level, if attempts to adopt the current scientific literacy goals are to be taken seriously. The process requires the development of an awareness of the many aspects which characterise the nature of science, illustrated by reference to particular instances. In practice, this could take the form of a case study of the history of some field of science, with emphasis on the features which illustrate the philosophy, sociology and methodology of science in the construction of scientific knowledge. In essence, this requires a two-fold study: the nature of science and the history of science, both of which are inextricably linked.

### 4.2 Secondary School Science Education

In most secondary school physics courses (such as those referred to in the previous section) and associated textbooks, the work of scientists, if it is considered at all, is seen as being akin to that of servants, toiling away in an earnest endeavour to uncover the so-called ‘rules’ and ‘laws’ of nature which have always existed since the beginning of time. The possibility of creative input by a scientist is rarely recognized, and there is little recognition of the notion that science is the product of the scientist’s
mind and not an external artefact at all. The consequence of this is that students do not see science as involving both descriptions of events or observations, and explanations demanding hypothesising, predicting or inferring. This leads to unrealistic expectations on the part of students regarding what science, technology and scientists are able to do. An additional effect is that science and its pursuit are seen as having nothing to do with ethics, culture or social responsibility. It is portrayed, at least by inference, as an objective, abstract exposé of facts and laws which already existed before scientists began studying them. Smolicz and Nunan (1975) advocated the “demythologising of school science” to avoid this superior ideology of scientism.

One of the exceptions to the content-driven approach in science education was exemplified by the Harvard Project Physics Course (Holton, Rutherford and Watson, 1973) which was developed in the late 1960s and early 1970s. In that course, some attention was devoted to historical aspects of each area of study, and it contained implications for the nature of science, as an integral part of the course. This research approaches science education from an earlier stage in its preparation. It proposes a science curriculum design framework which incorporates important features of the nature of science examined within the history of science. This will provide teachers, and others involved in curriculum design, with a means of developing courses which deal with the aspects of scientific literacy outlined in chapter 3. The resulting course may be similar to those such as the Harvard one, but the importance of this thesis is that it provides the framework for curriculum development rather than presenting the final set of curriculum resources as a fait accompli.

Science course descriptions and textbook presentations depict a particular view of the scientific process even though they do not explicitly discuss it. Often these have represented science as a one-dimensional study of concept and theory development, leading inexorably forwards, with occasional errors being corrected by more precise research, towards a fuller description of the truth, through the undertaking of experiments constructed and executed objectively. McComas, Almazroa and Clough (1998) commented on the limiting effect which such textbook and teacher presentations have in conveying a view of the nature of science to students. The impression of science which the school student gains from taking such a course is further entrenched if their teacher’s tertiary science training was only in
the traditional courses designed for future research scientists. In effect, these courses result in the socialisation of the science trainee into the scientific community. Cross (1997) certainly found that to be the case for teachers he interviewed in Scotland and Connecticut. He noted that

apart from science teachers’ personal experience of having to struggle to gain the required results in the laboratory, they have little experience of the production of science. (p. 613)

In the author’s experience, a similar situation also prevails in Australia in that the vast majority of teachers have little background in, or experience of, the history, philosophy or sociology of science. There is not normally any strong focus on studies about science in undergraduate science courses in Australia, and these are the courses from which future science teachers are recruited. Throughout their training, they are unlikely to gain any understanding or appreciation of the way science is performed or the process of scientific knowledge construction, although tertiary students who eventually turn to careers in science may well gain that awareness through direct involvement. Once teachers are ‘in the service’ there are pressures which mitigate against the possibility that they might review their understanding of science and the way they portray it to students. These pressures include the time available to teach a course, the breadth of that course in terms of content (which is often prescribed by educational authorities and hence limits the teacher’s ability to explore new directions), the expectations of schools in terms of examination results, and the student/parent/school/society understanding of what a science course should contain. This exacerbates the lack of knowledge about the nature of science which undergraduate students might otherwise gain through a study of History and Philosophy of Science at university (Mellado, 1997). These factors all conspire to make it highly unlikely that a teacher will design a course which challenges students’ appreciation of the nature of science and its history. Unless there is a conscious effort on the part of the teacher (or, more importantly, curriculum developers in the first instance) to address such issues, then the way in which a concept is explained by textbook authors or teachers is likely to be seen by students as the way in which the ‘science’ has actually developed. The approach which is chosen by authors or teachers as being the most appropriate for the development of a topic in order to best enhance a student’s understanding of current theory will not necessarily correspond to the way in which the theory actually developed during the course of history.
Students need to see science as being fundamentally a human activity rather than as a process of uncovering of pre-existing laws and facts. They need to see that science is an area of knowledge which develops from essentially personal investigations of natural phenomena. The style and methodology of these investigations change qualitatively over time. The knowledge which they produce is dependent on a range of factors including social and psychological components. Student understanding can begin with a realisation that different forms of science have existed and continue to exist in different cultures or in different eras. Aikenhead (2001) has demonstrated how such cultural issues can be dealt with at the school level with regard to indigenous cultures in Canada. An understanding that there have been different ways in which people, even within Western society, have observed and explained nature can be an early stage in having students contemplate what their concept of science is and on what evidence they base their view. Some examples of these are discussed further in the next section.

4.3 The Conventional View of Science

The understanding of Western science and how it develops, as seen by the general population, does not necessarily agree with the views of academics who are interested in science and the scientific process, nor is it in accord with the way many scientists themselves see the enterprise in which they are involved. Harris (1996) referred to “the popular view”, and recognised that “philosophers and often scientists themselves” adopt the view. He summarised its main thrust by describing its view of a scientist as someone who

sticks to the facts … [which] are obtained by direct observation … [and from which] he proposes hypotheses … which can be tested by further observation … .
The outcome of this method is a body of scientific laws … .
The steady advance of science is assured by this method because it adheres to the facts and abjures prejudices, preconceptions, and wishful thinking … . (p. 19)

As Chalmers (1976) observed, “it is a widely held belief there is something special about science” (p. xiii). Woolgar (1988) made similar points, employing the term “the ‘received’ (or standard) view of science” (p. 26) to refer to the idea that science is the objective study of the world and that scientific knowledge is a set of true statements about the “actual nature of the physical world”. Scientific reasoning, research and knowledge are held in particularly high regard, not only in everyday life but also in academic circles where, Chalmers noted, many areas of study “are
described as sciences by their supporters, presumably in an effort to imply that the methods used are as firmly based ... as a traditional science”. Bloor (1976), in describing how he proposed to examine the nature of scientific knowledge, suggested that “surely, we can do no better than to adopt the scientific method itself” (p. ix). Ziman (1968), in contrasting science with other fields of human endeavour, considered that “(s)cience ... is rigorous, methodical, academic, logical, and practical” (p. 1). At the time of writing his *Scientific Knowledge and its Social Problems*, Ravetz (1971) observed that “the public appreciation of science leaves nothing to be desired. ... ‘science’ reigns supreme” (p. 12). More recently, Wolpert (1992) referred to the public image of scientists as being

as stereotyped and inaccurate as ever: when not crazy, they appear bedecked in a white coat, wearing spectacles, and wielding a test-tube. The media usually present scientists as totally anonymous and character-free and give little insight into the way in which they work. Scientists are perceived as ... interested only in facts and yet more facts, the collection of which is the hallmark of the scientific enterprise. ... Also misleading is the idea that there is a ‘scientific method’ that provides a formula which, if faithfully followed, will lead to discovery. (p.x).

These descriptions of science present a clear contrast to the views which can be gained by a more critical study of what science is and what scientists do. Any science curriculum development initiative needs to take into account the current public understanding of science and whether it corresponds to that of students also. Such curriculum development needs to incorporate a critical analysis of the appropriateness and accuracy of such views of science, while examining the nature of science as discussed in overview throughout the remainder of this chapter.

4.4 *Sciences And Societies*

One aspect of seeing science and science education from a different perspective is to recognise that different cultural groups have developed ‘different sciences’ - different ways of observing, interpreting and explaining the world. Each society judges its own science by its successes, not by its failures or shortcomings. It considers its science to be ‘right’. Conversely, when describing or comparing the science of another society, there is a tendency to look at the failures of the other. Western society adopts that view and other societies do likewise. In science education programs, it is important for students to understand that the view of science which they develop is also likely to be formed in the same way and that it is not appropriate
to consider a ‘right’ science or ‘correct’ scientific knowledge. Research into the role which the ‘science’ of a society plays and the standing which it has in different societies, and in different eras, has been widely published. During the twentieth century, there have been approaches to science which have been founded in environmentalism and feminism. Significant starting points for such studies include Needham (1961) for Chinese science, Capra (1975) for a spiritual Eastern perspective, and Merchant (1980) for a feminist view of nature. Wertheim (1997) examined the inherent ‘masculinity’ of Western science as it has been practiced. The more recent the era the more likely it is that the processes of science and its development can be studied from a human involvement viewpoint, because there is more chance that the richness of interpersonal contact and the finer detail of social influences might have been recorded and still be available for examination and analysis. The analysis undertaken in this chapter is predominantly based on a broad overview of the characteristics of science as demonstrated in ‘Western society’ since about 1600.

4.5 Philosophies of Science

4.5.1 A Perspective for Secondary Science Education

It is important for science educators to understand that there are and have been different ways of interpreting science and that their own perspectives should be determined and compared with contemporary views on the matter. A conscious realisation of one’s own position is essential to prevent inappropriate or unintended views from being acquired by students or to challenge views they might already have. An understanding of some philosophical standpoints enables a more rational and orderly examination of events which take place over a period of time in science. This then assists in analysing and more fully understanding those developments. Studying some philosophies of science in this way suggests that a detailed study of the discipline is not required, but an awareness of some significant and recent views and interpretations is appropriate.

Philosophy of science is concerned with describing the rationality and developmental processes of science In some cases, the description is prescriptive (Losee, 1987), indicating what the processes of science should be. For example, around the time of the Scientific Revolution in the seventeenth century, Bacon and Descartes separately provided differing prescriptive views of the scientific process by
outlining a methodology which was based on formal practical inquiry and rational argumentation (these ideas are expanded on in further detail in Chapter 7).

In other cases, the analysis of science is descriptive (Losee, 1987), explaining how science is carried out. Examples of this include works by Kuhn (1970a) and Lakatos (1970) who offered interpretations of the way science takes place and how scientific knowledge changes. Their contributions are discussed further in section 4.5.2. Much earlier, Whewell (1858) examined how the application of Bacon’s philosophical approach had been applied in various fields of science to produce the then-current state of knowledge.

Other commentaries on science are a form of meta-analysis, examining what these various views of the scientific process imply about the perceived relationship between the natural world and the scientific enterprise. These could be thought of as philosophies of scientific knowledge. A view of science which was prevalent during the first half of the twentieth century is referred to as positivism; since about the 1960s, there have been alternative frameworks, described as post-positivism, which have been relied on for analysing science. Subsequent sections examine these interpretations.

4.5.2 Positivism

Positivism, in various forms, was a prevalent meta-analysis of the character of science and views of scientific knowledge until the latter half of the twentieth century. Some of its features can be described as follows:

- science involves systematic progress towards the truth of all aspects of nature by the (usually) steady accumulation of objective knowledge, which had its own hidden existence until discovered (uncovered) by a skilful scientist.
- ‘nature’ is governed by ‘laws’, new ones of which are proved or ‘discovered’ (see section 4.1) from time to time.
- if two scientists conduct the same experiment at different times, they will still observe the same things and draw the same conclusions unless one of them makes a mistake.
• on occasions, some aspect of science will be proved to be wrong by more careful measurement.

• theories are early stages in the eventual development of a scientific law.

• such universal laws can be arrived at by induction from observations.

• scientific knowledge results from the application of a rational and objective approach to an empirical methodology.

Laudan, Laudan and Donovan (1992) discussed similar characteristics when they referred to “the positivist or logical empiricist image (of science)” (p. 4). Chalmers (1976) used the term “naïve inductivism” (p. 2), and Woolgar (1988) described what he called the “received view” in a similar way. Science is distinguished from other activities through what Woolgar called “the principle of verification” (p. 16).

These and similar views of science were widely held until at least the 1950s and are still to be found today. For example, Mellado (1997), in providing a number of research citations, observed that their common conclusion was that “many investigations set most science teachers firmly in the framework of positivism” (p. 333), although he also suggested that the actual situation was probably more complicated than that. Ziman (1968) scathingly referred to the view which people develop of the “irresistible power and automatic progress of Science” and of the “doctrinal mechanistic positivism”, both of which are “so properly deplored by men of sensibility and sense” (p. 72).

From around the early 1960s, problems began to emerge with the positivist philosophy and the apparent simplicity of the process of production of knowledge was questioned. Laudan (1996) offered an analysis of the situation. Views were raised suggesting that there was something of interest and significance regarding the processes which occurred prior to the publication and ultimate acceptance of a piece of scientific knowledge. The final piece of scientific knowledge was seen to be not a unique and inevitable consequence of a set of initial observations or given conditions. There was a realisation that many factors influenced the way in which the final piece of scientific knowledge was described. This new conception of the scientific process has been as broadly described as post-positivism or relativism, or even by Laudan (1996) as “postpositivist relativism” (p. 3). Two of the principle lines of thought in
this new philosophy were based on a sociology of science and a constructivist view of knowledge production. Ziman (2000, p. 232) provided a careful analysis of this “direct counter to naive scientism”. Supporters of both paradigms recognise the importance and relevance of human involvement in the production of knowledge. The former term alluded to the interactions which occurred between interested parties in making observations and in the drawing-up and refinement of theoretical proposals. In addition, there was a recognition of the importance of the influence which each person’s views and status had in those processes. The latter term developed from a view that knowledge frameworks were ultimately personal and individualistic. In extreme forms, constructivism became an almost unworkable concept in that it suggested that any one person’s view (construction) of the world was so unique and personal that it could not be known by anyone else and so there was no basis for common discussion - views were essentially incommensurable. Matthews (1994) advised caution in adopting an uncritical acceptance of constructivism, particularly as it might be applied to any of its more radical interpretations to the field of science education. Less extreme positions on constructivism (for example, Northfield and Symington, 1991) indicate educational approaches which may be more widely adopted.

Another conceptualisation of these new philosophical directions in science was referred to as relativism. The term has been used to describe a ‘methodology’ of science as well as describing how a scientific statement might be interpreted. This latter connotation stood in contrast with the positivist notion that there was an ultimate ‘truth’ which it was possible to strive for in all areas of philosophy, including that of science. The relativist view held that it did not matter whether there was such an ultimate truth or not. If a contextual framework was at least able to describe an existing set of phenomena then the need to establish ‘truth’ was immaterial - efficacy rather than truth was the determinant of success and progress. In other words, if ‘it worked’ then that was all that was required.

These changes in philosophical emphasis began to emerge through the ideas of Kuhn (1970a), Popper (1968), Lakatos (1970) and Feyerabend (1975), among others, during the 1970s. Although there were points of overlap and divergence between their respective views, they were all interested in examining the process of knowledge development. They understood that it was more than simply an inevitable
and progressive uncovering of a series of layers resulting in the exposure of ever
greater amounts of knowledge, as was implied in the earlier positivist viewpoints.

4.5.3 Postpositivism

The theoretical framework used to explain any set of related phenomena often
changes to some degree or other over time as more detailed measurements or
observations become available, or for a range of other reasons. The characteristics of
the process of theory refinement and change have been discussed by many people, the
most notable in the last half of the twentieth century including four of the people
mentioned in the previous section (Kuhn, Popper, Lakatos and Feyerabend). These
four all viewed the process of theory change differently but they have all been
considered as postpositivist philosophers of one sort or another. Laudan (1996)
provided a detailed analysis of their contribution and influence.

It was Kuhn’s view that most science activities involve confirming what has
already been announced, or adding breadth to the observations or measurements
which have already been made. Kuhn (1970a) referred to the process of doing
“normal science” which involved the application of a generally accepted theoretical
framework called the “dominant paradigm”. This framework was, according to Kuhn,
strongly adhered to until another was proposed and widely accepted within the
scientific community. This period of change was referred to as a ‘revolution’. He
suggested that the revolution took place as a result of discussions between important
scientists whose respective influences among each other determined the form of the
new framework. According to Kuhn, the interim period of change - the revolution -
arises as a result of an alternative framework being proposed, and not because of a
breakdown of the current framework. The newer theory is not usually completely
established as the dominant paradigm until the older scientists who subscribed to the
earlier theory are no longer active. Having worked with the older framework for a
significant period of their scientific career, scientists are reluctant to retract all the
arguments which they have put forward, and to discount the confirming work which
they have undertaken in support of the earlier theory unless there is no way their
theory can be sustained. And even then, any change in allegiance comes only slowly.
To do otherwise would be to admit that their extensive investment of time and effort,
undertaken throughout a sometimes long career, has now become worthless. Kuhn’s
analysis of scientific progress in its evolution and revolution emanated from a sociological view of the scientific enterprise.

Lakatos (1970) described the processes of science from a more structural viewpoint. He wrote of “research programmes” built on a “hard core” surrounded by a “protective belt” of hypotheses and theory constructs which became the focus of research investigation and modification if necessary, keeping the core as “irrefutable” (p. 133). As work proceeded in an area, the protective belt may change, but if the core had to be changed then that particular research programme fell into disuse. Discrepancies (“anomalies”) between observations and the theory structure of the programme were allowable as they were not seen as a direct and immediate challenge which had to be dealt with. They could be held aside for a time until they might be incorporated in further developments of the protective belt and so the research was able to continue without having to address each anomaly as it arose before further progress could be made. For much of the time, more than one research programme could be current but eventually one programme would dominate and the others would fall away through the lack of “positive heuristic” driving it forward to produce “novel facts” (p. 155). In the end, Lakatos also included a sociological and political dimension in his analysis of scientific processes when he referred to research programmes “supported by talented, imaginative scientists” or “stubborn defenders” (p. 158). The point on which he was in agreement with Kuhn was that he considered that science does not proceed by “accretion” of facts, and that it is important to understand how scientific knowledge comes about.

Popper (1968), in the *Logic of Scientific Discovery*, discussed hypothetico-deductive methods and falsification largely as a response to the separate problems of induction and demarcation. As the title of his main work indicates, he was primarily interested in logic as the basis for any explanation of the construction of knowledge; in his view, scientific statements are “submitted ... to logical examination” (Popper, 1968, p. 86). He saw as “irrelevant to the logical analysis of scientific knowledge” (op.cit., p. 85) the process by which any scientific statement arises, the way in which the first enunciation of a statement of theory came to a scientist, consigning that to study by psychologists rather than philosophers.
The Kuhn and Lakatos theses were both essentially descriptive, being based on science which had actually happened. By contrast, Popper proposed more of the ideal for the execution of scientific activity. His view was *prescriptive*.

The fourth person in this group of postpositivist philosophers is Feyerabend. All four people have made significant contributions to debates about the nature of science during the 1960s and 1970s, but Feyerabend’s thesis (1975) has been, in many ways, the most controversial. He was of the opinion that there are always historical exceptions which could be found against any of the methodologies proposed by others, and so he argued that there should be no single theory which could be used to describe the workings of science. His oft-quoted “anything goes” catch-cry (op. cit., p. 23) summarised his position.

The more recent sociological view of science asserts that scientific theory, which is the end result of scientific work, is not something which has arisen rationally, immediately, necessarily and inevitably from an observation. There is some scientific and human activity, which is not unimportant, and which occurs between observations and their incorporation into a scientific theory framework. This activity is what has become the focus of interest and study for students of science over recent decades and which is said to influence (or actually determine) the shape of the final framework or how it changes.

The foregoing discussion is not intended to be a definitive summary or produce a conclusion regarding the latest, or most favoured, philosophy. The essential point here, in the context of this thesis, is to highlight the notion that there are, and have been in the past, different ways in which people have viewed science and that some awareness of this idea is an important part of an education in science.

### 4.6 Science and Technology

The nature of science, in the sense of what defines an activity as being scientific, can be clarified to some extent by considering distinctions between science and technology.

Rose and Rose (1969) suggested that a distinction between science and technology on the basis of an understanding of the “laws of nature” as compared to “control over the world around us” (p.1) represents a dichotomy which does not accord with reality. They were of the opinion that “science and technology must be
seen as interacting terms; discovery precedes invention, and invention presages discovery - at least in our contemporary society” (p.2). Scientific advances and new technologies are dependent on each other. They noted that the acceptance of this “marriage of science and technology” (p.8) is only recent.

However Rose and Rose also noted the overlap which existed, in the early days of the Royal Society, between what they referred to as “pure and applied science” (p.14). They pointed to the numerous problems with some practical application which were studied by Society members. In those days, it was considered that a significant function of science was to provide material benefits – Merton (1970) recalled the term “the Comfort of Mankind” which Boyle used in his will (p.88). Merton also noted Bacon’s earlier reference to “the true end of scientific activity as the ‘glory of the Creator and the relief of man’s estate’” (p. 88.). Elsewhere, Bacon distinguished between “light-bearing experiments” and “fruit-bearing ones”. He refers to the former as being “of no use in themselves, (they) simply help the discovery of causes and axioms”; the latter type of activity he indicated as being undertaken “to reveal the natural cause of something” (p. 108). (Novum Organum, Book I, Aph. XCIX).

In a similar vein, Ziman (1984) spoke of the interdependence of “knowledge by research” and “benefits in material form” (p.119) when examining the roles of science and technology. In a different publication, Ziman (1976) employed the titles “The Art of Knowing” and “The Art of Knowing How” (p.3-4) for science and technology, although he was concerned that there should not be undue emphasis on “pedantic definitions” and suggested that:

[we should] allow the territories governed by each of these terms to shade one another and overlap without formal boundaries. (p.4-5).

Wolpert (1992) emphasised his view of the difference between the two when he stated definitively that “science produces ideas whereas technology results in the production of usable objects” (p.25). Cross and Price (1992) were also keen to emphasise the fundamental differences between science and technology, suggesting that questions about why and how are instructive in clarifying the contrast.

The term ‘technology’ was probably first introduced during the eighteenth century by Johann Beckmann (according to Inkster, 1991, p.29). This indicates that there was a perceived distinction between the types of activities undertaken by those
working in the scientific field, and that this differentiation must have been in existence for long enough to suggest the introduction of a new term. Nevertheless, at that time, the two activities were usually associated with the same people and the same journals. Inkster (1991) was of the opinion that, at least for those times:

there is little insight to be gained from an artificial separation of interests in natural science and interests in technique - the same publications and the same congeries were involved. (p.50).

In reference to the present century at least, Ziman (1968) considered that:

Science and Technology are now so intimately mingled that the distinction can become rather pedantic. (p.25).

Elsewhere in the same work he provided an illustrating example:

Suppose ... we are researching on the phenomenon of ‘fatigue’ in metals. We are almost forced into the position of saying that on Monday, Wednesday and Friday we are just honest seekers after the truth, adding to our understanding of the natural world, etc., [that is, we are scientists] whilst on Tuesday, Thursday and Saturday we are practical chaps trying to stop aeroplanes from falling to pieces, advancing the material welfare of mankind and so on [that is, we are technologists]. (p.23).

Igor (1994) assumed a spectrum incorporating science and technology (as did Dixon, 1973, p.210), and set engineering near the middle of the continuum:

(E)ngineers work in, and exploit, the scientific environment of the day, which they hope will continue to expand through the unfettered efforts of their scientific colleagues. ... Their science involves design - that elusive process of drawing on ideas from everywhere, including the science pool, and nowhere. ... At the end of the spectrum, technology stands to engineering in the same relationship as engineering stands to science: it lives in the pool created by the efforts of academic research engineering departments and the research laboratories of government and industry. (p.50).

These views illustrate that distinctions based on purpose characterise discussions of science and technology.

4.7 Science and Society

The institution of science does not operate in isolation. It interacts with other sectors of society on many levels. This can be seen to be the case not just in current times but also in past eras, in addition to other cultures. An appreciation of these connections is important in order to overcome any perception that science and
scientific knowledge is not simply something which exists and develops under its own impetus.

From one perspective, there is a significant dependence by science on society in the provision of financial assistance for scientific work to be carried out and this has been the case for centuries, within western science at least. Principally, these links occur with government organisations (including the military wing), industry and philanthropic organisations. As Medawar (1984) so directly expressed it:

Most scientist in most countries are funded directly or indirectly from the public purse. (p. 45)

On this larger scale, Price (1963) gives detailed commentary on the interactions between various groups and contrasts the twentieth century situation with that which occurred in earlier times.

Elsewhere Needham (1961), described in vast detail the scientific and technological culture and development which took place in China, in many instances before similar events occurred in Europe. He recognized also the work done in Persia and other Near East countries. It is not the function of this thesis to describe a full history of science as it arose in all cultures and so, while recognition is given to Chinese scientific history, this thesis focuses on the European developments as just one setting in which the characteristics of science can be illustrated. There is undoubted scope for similar research to be done to incorporate the scientific history of the Far East into a secondary school science course designed along the same lines as this research.

Often the science is actually in industry rather than just interacting with it, although it is at this level that the distinction between science and technology becomes most blurred, as was pointed out in the previous section.

Science is also connected with the wider society on a social level. Those working within science communicate their knowledge and understanding to others, and those from outside the institute of science can influence the directions taken by those within. There is a mutual interchange of ethical principles and moral arguments which takes place between both communities. Merton (1970) examined this influence in seventeenth century England. Some, such as Snow (1963) have lamented the lack of discussion in his time between scientists and others; more recently, the Royal Society (1985) have been significant among many organisations and individuals who
have encouraged clearer “Public Understanding of Science”. This two-way interaction is fundamental to the achievement of an individual and collective Social Responsibility among all people and institutions within society.

4.8 Science as a Society

It could be argued that science and the society in which it functions interact symbiotically. There is also a basis for considering the institution of science as being a form of society in its own right. Ziman (2000) stated succinctly that “academic science is a culture” (p. 24). Such a position can be proposed on the basis that the essential characteristics of a society can be recognised within the various operational features of the institution of science. Confirmation of this requires an analysis of societies to determine what might be their central characteristics, and to draw parallels between them and the processes of science.

In the context of this research, which focuses on science education at the secondary level, it is not necessary to demonstrate this “science is a society” connection conclusively and definitively. However the fit between the two structures is significant enough to consider it beyond the level of a rough analogy. The curriculum framework which is developed in Chapter 6 expands on this comparison, and argues strongly that the connections are sufficient for the “science is a society” viewpoint to be used as the basis for curriculum design. In doing so, there are numerous links established between the characteristics of science which are highlighted in this chapter and the characteristics of a society which are proposed in Chapter 6.

4.9 Sociology of Science

4.9.1 Beginnings of the Discipline

Sociological studies of science have become widespread in relatively recent decades. Bloor (1976) provided a detailed examination of the human factor in the construction of scientific knowledge. Before him, others such as Bernal (1939) and Ziman (1968) recognized the social character of science. According to Franklin (1995), Merton is “widely credited with “inventing” the sociology of science” (p. 167). Cohen (1990) similarly recognised Merton as the “most influential leader and spokesman” of the sociology of science in its early years during the middle decades of the twentieth century. More recently, Barnes and Edge (1982), Woolgar (1988),
and Mulkay (1991), among many others, have contributed to an examination of the various characteristics of the sociology of science.

Merton’s contributions to the sociology of science began with an examination of the causes of the scientific revolution in the seventeenth century (Merton, 1970), in what is generally referred to as the “Merton thesis” and has been examined in detail by Cohen (1990). Essentially, Merton linked the new directions of the Scientific Revolution to the influence of Puritanism. Puritanism emphasised a simple, practical, pragmatic and methodological outlook which determined the lifestyle and work ethic of its followers. While Puritanism did not actively encourage the approach to natural philosophy which developed during the seventeenth century, Merton argued that the latter was logically consistent with the former to the extent that there was a definite influence of one on the other. Subsequent to that study, the many aspects of the sociology of science which Merton examined included priority in discovery and the reward system within science (Merton, 1957), the characteristics of multiple discoveries (Merton, 1961), and the communication system which involved what he called the “Matthew effect” in awarding credit by one scientist to another (Merton, 1968). Although he initially studied the sociological aspects of science, he later concerned himself with the development of the sociology of science as a discipline of science in its own right. He described what he considered were the four “norms” of science - the ideals to which scientists and the institution of science attempt to aspire. Briefly, these are communalism (the idea that the results of scientific endeavours should be publicly available), universalism (the practicing of science by scientists is democratic in that any bias in opinions or actions is not acceptable), disinterestedness (the practice and outcomes of science are not influenced by personal interest or self-advancement of the scientist at the expense of other scientists) and organised scepticism (an acceptance within the institution of science that critical but fair debate surrounding new ideas is acceptable and to be encouraged). Additional norms have been suggested such as originality by Merton (1957) himself, and Riggs (1992) mentioned Barber’s suggestions of rationality and emotional neutrality.

Bloor’s examination of the sociological aspects of scientific knowledge resulted in what he himself referred to as “the strong programme” (because it made much stronger claims for the sociology of science than previous studies). His analysis is based on four “tenets” - causality, impartiality, symmetry and reflexivity - which
define his programme. Barnes and Edge (1982) supported the strong programme and provided examples of sociological analysis in a range of case studies. The strong programme has not been without its strident critics however, among them Laudan (1981).

In Riggs’ (1992, p. 124) commentary on science studies, he described two aspects associated with a social study of science: the sociology of science which is concerned with “the social network and hierarchy of scientists”, and the sociology of scientific knowledge which recognises that scientific knowledge is not dealing with certainty and that the type of knowledge which is produced is at least partly determined by social influences. Ziman (2000) recognised a similar partitioning. Science is a “social institution” (Ziman, 2000, p. 4) and it is embedded within a wider social institution both of which have mutual influences on each other’s progress. And, in addition to studying those influences, he also recognised the value of studying how scientific knowledge comes about: “scientific knowledge is not just a disembodied stream of data or the books on a library shelf”.

4.9.2 Social Structure in Science

The social structure of science, and the changing form of that structure, can begin with a study of the number of people directly involved in the production of a piece of scientific knowledge. Initially, natural philosophy, as it was then called, was studied at the level of the individual (Descartes and Newton are two early examples of this within the field of optics, for example). Adequate personal finances or some social or royal benefactor were able to provide sufficient income for daily living and for conducting researches (further discussion of living conditions at that time are included later in section 7.3.4). Natural philosophers were largely free to undertake whatever research they wished. Then small teams which were centred in particular universities became common in the early twentieth century (Rutherford in the Cavendish Laboratory at the University of Cambridge, for example). The larger the research group, the greater was the demand for some external source of funding and this ultimately resulted in conditions on the type of research which was funded. As the twentieth century progressed, even larger research projects have become more commonplace, particularly as a result of two world wars, so that very large groups of scientists were required to solve problems urgent to the war effort - sonar in the First World War and the radar in the Second World War are two examples in the physics
area. Snow (1969) described the inter-relationship between science, government and industry in the development of radar. Rose and Rose (1968) described the distinctions between, and characteristics of, “Big Science” and “Little Science” - the terms they used to refer to the characteristics of science at either end of the size scale. The larger the research group size and the greater the complexity of research project, the more the distinction has been blurred between science and technology.

4.9.3 Social Construction

Scientific knowledge is generally only produced or changed as a result of interaction between people. This communication may be indirect via books and journals, in which case the readers and writers do not need to be contemporaries for the ideas of one to influence those of another, or to prompt a line of investigation by another. At this level, the influence is effectively a once-only affair. But written communication can also be more personal, direct and on-going. Early examples of this can be seen in the development of theories of light in the early 1600s. Descartes and Fermat conducted lengthy discussion and debate via letter, generally through an intermediary, Mersenne, who was able to coordinate and interpret communication between these two and others interested in optics (Sabra, 1981). Such communication became more formalised with the publication of journals by scientific societies such as the Royal Society. An early illustration of the interaction between people as an important factor in developing an understanding of nature can be seen in the communications between Newton, Hooke and others through the pages of the Philosophical Transactions (the Royal Society’s journal) or using Oldenberg (the secretary of the Royal Society at the time) as an intermediary (Sabra, 1981).

Since that time, communication between scientists has expanded and evolved to the point where Ziman (2000) has commented that

the web of lectures, examinations, seminars, conferences, papers, citations, referee reports, books, personal references, job interviews, appointments, prizes, etc. in which my scientific life was entangled … must have some influence on the work I was doing. (p. ix)

Conventional science courses or texts devote little space to the idea that scientific knowledge is a product of the interaction between people. Wilkinson (1999) has provided examples of this omission in relation to physics texts commonly used for years 11 and 12 students.
4.9.4 The Psychology of Science

An appreciation of the sociology of science outlined in the previous section provides information essential to a fuller understanding of the nature of science and its processes. Psychological aspects of scientific activity have been referred to, or at least implied, by Kuhn (1970b), Popper (1981), Lakatos (1978), Hanson (1958), Polanyi (1958) and others. Kuhn, in reference to the factors which may influence scientific progress, noted that “it should be clear that the explanation must ... be psychological or sociological” (p.21). Elsewhere in the same publication, Kuhn indicated his understanding of the personal and subjective aspects of scientific development when he states that his “recourse has been exclusively to social psychology (I prefer ‘sociology’)” (p.240). Kuhn also spoke of the “gestalt switches” which can occur in thought processes and in the perception of data. The term originates in cognitive psychology and that discipline may throw some light on the way in which that phenomenon occurs, in the Kuhnian sense. Popper referred to the “psychology of knowledge”, and to his opinion that the development of a new scientific theory in a person’s mind is part of the realm of empirical psychology (although, having said that, he then eliminated such considerations from any further discussion of the development of scientific knowledge, being interested only in what takes place after the new theory has been stated, rather than what influences its initial formation). Lakatos recognized the relevance of aspects of psychology in explaining why scientists change from one research programme to another in search of a more attractive positive heuristic: “the history of science cannot be fully understood without mob-psychology” (p.55). The view that there is a psychology of science has been one of the directions in which some researchers have moved since the beginnings of postpositivism. As Houts (1989) pointed out:

To say that the psychology of science was not well received within positivist philosophy of science is an understatement ... (p.56).

This implication (by Kuhn and those mentioned above) of the possibility of a psychological basis for the way in which at least parts of science were done did not translate immediately into the construction of a psychology of science, per se. That was not the purpose of the work done by those philosophers.

Shadish and Fuller (1989) approached the concept of psychology of science by referring to other areas of metascience: history of science, philosophy of science
and sociology of science. They suggested that the first two disciplines began near the start of this century, and the third emerged around the middle of the century. But they concluded that the “(p)sychology of science seems to be, tentatively, just now emerging as a recognized speciality” (p.3). Houts (1989) was reluctant to set the psychology of science as yet another way of examining science:

there is little doubt that the benefits to the scientific community will be proportionately reduced just to the extent that psychologists succeed in establishing “the psychology of science” as yet another disparate field. (p.80)

Rather he suggested that there are some areas within the scientific enterprise which can legitimately (and perhaps only) be discussed by the psychology of science. To this end, Houts outlined sets of questions on (1) theory change and development, (2) constructivist epistemology with an individual focus, (3) history of science, (4) the norms of science, and (5) the sociology of science, which could form the basis of “identifying a positive agenda” (p.62) for the psychology of science.

Maslow (1966), in recognising the psychology of science as a relevant field of study, set it in a separate category when he virtually excluded it from the reflexivity concept which has become an essential feature of metascientific disciplines - that is, the theory structures they produce must apply to that discipline itself, as well as to science generally. Provable (or falsifiable) predictions derived from some theory structure are widely seen as important features of a scientific discipline (the views of Lakatos and Popper are examples of this notion). Maslow, however, suggested that “prediction” is a wholly undesirable characteristic for a psychology of science: “(h)ow could it be seriously said that our efforts to know human beings are for the sake of prediction and control?” (p.40).

Barker (1989) raised a different reflexivity problem in relation to the psychology of science - one associated with the use of a scientific explanation (as would occur in the psychology of science) to explain a scientific explanation (that is, one which occurs in, say, physics where a particular theory is used to explain some observation). He overcame the difficulty by relying on two arguments. Firstly, “other disciplines with well-developed bodies of technique” (p.108) apply those techniques to study themselves in a way which is regarded as “legitimate” and “uncontroversial”. Secondly, he referred to the “mistaken notion of the possibility of defining a practice by means of constitutive rules”. In a footnote (p.111) he also suggested the possibility
of “local” rather than “global” methodologies in science, so that the methodologies of physics, say, do not have to apply to psychology.

Shadish and Fuller (1989) proposed a number of benefits which the psychology of science could produce, among these they suggested that “psychological theories could suggest new applications of (psychologists’) theories to the various dimensions of scientific work” (p.12). Their examples included using current understandings of cognitive processes to improve reasoning strategies of scientists, and applying the results of social psychological research to produce more effective decision-making processes within a group of scientists who are discussing competing theories or the implications of experimental results.

More importantly, from the point of view of this research, is the contribution which the psychology of science can make to metascience, and the implications which that has to a clarification and study of the nature of science in secondary science curricula.

4.10 **The Processes of Science**

There are many characteristics of scientific processes which could be examined but, as was mentioned in section 4.1, it is not the purpose of this research to develop a comprehensive analysis of the nature of science. Accordingly, some important aspects of the process of science which are discussed here include its epistemology, the meaning of discovery, and the significance of experimentation.

4.10.1 **Knowledge Production**

The processes of science could be considered to begin at the personal level and then progress through stages to widespread general acceptance. In terms of knowledge production, science generally begins with an individual scientist or at least a very small group of people. Evidence about some aspect of the real world is collected. These observations may then lead to hypothesis testing which, if successful, leads to a more public “discovery claim” as it is described by Woolgar (1988). After wider examination and scrutiny at the institutional level, this tentative new knowledge may gain wider acceptance and eventually attain a more permanent status. Hodson (1981) used a similar model proposed by Ravetz to draw together three different philosophical views on scientific knowledge: the subjectivist,
objectivist and the consensus views. Turner (1996, p. 156) referred to Bertrand Russell’s description, in *The Scientific Outlook*, of the shift which occurs from the first to last of these stages in “arriving at a scientific law”. Russell (1931) spoke of the observation of

significant facts … (and) arriving at a hypothesis which … would account for the facts … (and) deducing from this hypothesis consequences which can be tested by observation (p. 58)

The discussion by Turner was in the context of the selectivity which necessarily takes place at each stage with respect to decisions such as what to research, what to observe, and what hypothesis to propose. This selectivity is one of the characteristics which underlies the more overt processes of science.

Often research does not produce evidence which results directly in discovery claims, or new or amended theory structures. It may be that research provides results which are anomalous in terms of the current paradigm, and may be dismissed either after, or without, more detailed examination by the scientist.

Anomalous results may provide the stimulus which initiates new directions of research, particularly in the hands of someone who is, in some way, predisposed to challenging either their own observations or the dominant theoretical structure appertaining to those observations. It is at this stage that a “revolution” (in Kuhn’s terms - see section 4.5.3) or a new “research programme” (in Lakatos’ terms - also in section 4.5.3) may begin.

On the other hand, there is the situation where anomalous results may be deemed “suspect” for a variety of unspecified reasons as explained by Polanyi, (1946, p.117) and so dismissed without further thought. It is inherently difficult to find out about this work, which is nevertheless part of what constitutes the process of science, because it is normally only at the discovery-claim stage, which only occurs after any initially suspect results are disposed of, that any public reporting occurs. Ziman (1968) recognised the importance of this “transformation between the personal and the public” (p. 33). It is this latter process which provides the opportunity to investigate aspects of research. Until that happens, opportunities for investigation of any methods and influences which may characterise science are limited. The alternative to waiting for publication is to undertake some form of first-hand observation of an institution or scientist to study methods and influences, as has been
done by Latour and Woolgar (1979), for example, in their research when Latour arranged to become a member of an investigation team.

After new scientific knowledge has been proclaimed, later events may continue to confirm that knowledge by direct examination in further research (the carrying on of ‘normal science’ as Kuhn would describe it, or, in Lakatos’ terms, the maintenance of a ‘positive research heuristic’) or by the lack of anomalous results in research derived from that knowledge. But it is also possible that later events will show that the newly-proclaimed scientific knowledge was either not new (that is, an earlier priority is established so that the later knowledge-claim added nothing new to the store of scientific knowledge) or it was false. The “cold fusion fiasco” (Huizenga, 1993, p. 236) is a good example of the latter. This situation arises when either both, or just the second, of the following conditions occur: firstly, the research evidence was found to be incorrect (there was deliberate or unintentional misreporting of observations or misinterpreting of results, and this was subsequently realised when attempts were made to replicate the work or to extend the results of the work); and secondly, falsifying evidence was produced.

The first condition, on its own, is insufficient to remove a statement from the store of scientific knowledge - there have been many pieces of accepted scientific knowledge which were subsequently found to be derived initially, at least partly, from evidence which was dubious for one reason or another. Ziman (1968) discussed aspects of this possibility in his chapter on “Scientific Method and Scientific Argument”. The knowledge remains nevertheless, at least for a time, because predictions derived from it and subsequent testing continue to be supportive. In other words, a statement is accepted as scientific knowledge not because of what happened before it was produced, but because of what happens after it has been produced. Classic examples of such situations can be seen in cases such as that of Millikan whose selectively chosen experimental data resulted in his conclusion that electric charge was quantised, or Mendel who appeared to discount some pea plant results which did not fit his initial hypothesis. In Mendel’s situation, there are contrasting views on what he may or may not have done with his results, thus illustrating that the study of the processes of science is itself not without controversy and its observations, like those of science, are also theory-laden. The conclusions of both scientists have persisted, essentially in the form first proposed, even to the present
time, despite what occurred before the discovery claim was put up for public scrutiny and persisted afterwards, not because of the initial experimental work, but because of the subsequent explanatory and/or predictive success of the theoretical framework which was proposed. None of this is surprising, however, to those who believe that all scientific knowledge is tentative (for example, McComas, Almazroa & Clough (1998) and Bauer (1992)).

If only the second condition applies (that is, the production of falsifying evidence), a “new store” of scientific knowledge may be created. The falsified knowledge is not removed altogether, but remains in the “old store”, being perhaps still useful in a limited set of circumstances. The relationship between Newtonian mechanics and Einsteinian relativity illustrates this point.

When both conditions are met (initial evidence incorrect or misinterpreted, and falsifying evidence is subsequently produced) and the falsified knowledge was derived from unintentional misreporting, it also remains in the “old store”. But if the new knowledge was found to arise from deliberate misreporting, it is classified as “fraud” (for example, the Piltdown Man case as discussed by Straus, 1954) and it is removed from all stores of scientific knowledge, with some embarrassment to the institution of science and to those who, in good faith, had accepted it.

4.10.2 Discovering in Science

The previous section described various ways in which scientific knowledge can be produced. Kruglanski (1994, p.211) suggested that a primary function of science “could be the construction of new knowledge”. Brannigan (1981, p.13) interpreted Hanson’s understanding of discovery as “the reorganisation of the value of an object or fact or pattern, in terms of a more comprehensive system of relations by which it is seen to be defined and circumscribed”. The two ideas are equivalent in that the notions of construction and new are contained in the meaning of reorganisation.

In the decades from the 1960s to the 1990s, in Victoria at least, the focus of physics courses in secondary education has been almost solely on concept development and theory comprehension, with some incorporation of practical applications in selected contexts. There was little reference to, or recognition of, where and how the concepts and theories arose. In many texts related to that era the
notion of *discovery* is not suggested. When the term is encountered in school textbooks, its use often simplifies the role of scientists by implying that they have *uncovered* a previously hidden law. Statements such as “Coulomb …discover(ed) the inverse square law of force” (Storen & Martine, 1987, p. 384) are made which convey, perhaps unintentionally, the impression that the law was already in existence and the scientist found it. Woolgar (1988) suggested that

> the metaphor of scientific discovery … is precisely that of uncovering and revealing something which has been there all along (p.55)

The position adopted in this thesis is that scientific knowledge is something *created* by people not *discovered* (in the above sense of the word) by them. Phenomena in nature are characterised by various features which are determined by the observer. Any ‘law’ which arises from those observations is the result of how the scientist uses the current paradigm to find a common thread in a set of observations. It is in this way that a law is discovered, rather than by uncovering something which was pre-existing but unknown as is often the implication when, for example, the phrase ‘a law of nature’ is used.

There needs to be some distinction made here between two possible meanings of the term *discovery*. On the one hand it can be used in the general sense of finding something - a hidden or lost item, a new island or species, or an artistic or sporting talent, and so on. In this sense, the item which is discovered has an existence of its own, independent of the discoverer. Ziman (1968) referred to this as a “vulgar definition” of discovery (p. 48) and it is often this meaning which is conveyed about discovery in science. This type of discovery is not without merit, nevertheless. Nor is it completely unaffected by human creativity. Ziman (1968) described various forms of discovery:

> Discovering an X (e.g. a comet), discovering X (e.g. oxygen), discovering that X (e.g. electrons disport themselves in an undulatory manner). (p. 48)

These are all examples of processes which demonstrate some creative influence of the discoverer, but an understanding of that influence is only possible if there is some examination of the process of discovery. Alternatively, the term can also be used to explicitly suggest creativity on the part of the discoverer. Production of ideas falls into this latter meaning of discovery, but not into the former. It could be argued that, once such a mental construct is discovered in this latter sense, it does
gain an existence of its own, (Popper’s “third world”) although clearly this is not the same sort of existence as the objects which are discovered in the sense of the first meaning. Again, Ziman (1968) commented on this alternative interpretation of discovery by likening it to something “unexpected, unusual, striking” (p. 49). He suggested that discovery is a break with “the monotony of conformity” and that it is “of the utmost importance in Science” and, in this sense of the word, it is

the means by which vague, general, untested notions are made explicit and brought into consciousness for acceptance or rejection. (p. 50)

For those who are engaged in teaching science, it is important to understand these two different meanings as the term is one which is widely used in discussions within the history or philosophy of science, and often misused in less academically rigorous contexts. The sense in which scientific knowledge might increase as a result of uncovering facts, theories or laws which had been waiting to be discovered, as it were, conveys a very different view of science to that which acknowledges the creative input of people which produces the science. The latter approach accords a more appropriate value to the contribution made by scientists, and enables a simpler framework to be constructed to explain the accumulation of scientific knowledge and particularly the revolutionary changes which occur from time to time.

Discovery processes have been discussed by Popper, Kuhn, Brannigan, Lamb and Easton, and Woolgar, among many others. Some of the points they make and which are important to consider in science education include the following:

- there is no such thing as a logical method of having new ideas (Popper, 1968, p. 31-32)
- any attempt to date the discovery [of oxygen] must inevitably be arbitrary because discovering a new sort of phenomenon is necessarily a complex event (Kuhn, 1970a, p. 55)
- social understandings are central to the status of scientific discoveries (Brannigan, 1981, p. 164)
- the process of discovery … evolves according to a logic that accompanies it. As more information is advanced, contradictions acknowledged and ironed out, a discovery evolves together with criteria which render it plausible and later acceptable (Lamb and Easton, 1984, p. 44)
- discovery is a process rather than a point occurrence in time. It is a process of planning, anticipation, soliciting support and obtaining institutional approval of a claim or definition (that a discovery has occurred). (Woolgar, 1988, p. 58)
The concept of discovery has conveyed different ideas over time and across society. Brannigan (1981, p.2) referred to the “iconic image of discovery”, using the Archimedes ‘eureka’ incident as the definitive case. He also described discovery in the “popular images of science” as being “shrouded in a shell of mystery” or occurring as a result of the “eccentricity of a historical personality”. Within the ‘popular images of science’, when some recognition is attributed to a scientist for discovering something, a process of discovery is not suggested. The implication is that the time period involved was short, perhaps even instantaneous - akin to a gestalt shift or a eureka event. Brannigan referred to a number of these such as Einstein and the concept of general relativity, and Kekulé and the benzene structure, as well as Archimedes and the law of hydrostatic displacement. Sudden occurrences do occasionally result in a useful and progressive reconstruction of a set of related phenomena. But that should not be the only impression given regarding the discovery process. Brannigan recognised that the historical accuracy of reports of such events may be questionable and the resulting discovery process is

often shrouded in a shell of mystery and/or irrationality … or in the eccentricity of a historical personality. (op. cit., p. 2)

He suggested that this may have been the inadvertent consequence of the view of philosophers such as Popper and Reichenbach who separated the process of discovery from its later publication and justification which they considered a reconstruction of the earlier process. The study of the “act of discovery” was then set aside and so perhaps resulted in it being regarded as some mysterious process in the popular view.

Lamb and Easton (1984) particularly commented on multiple discoveries and the high frequency of them. They pointed out that discoveries often result from a readiness within a section of the scientific community which is undertaking research in a particular area. With so many minds focussed on an issue, they suggested, it is not surprising that more than one person or research group might arrive at a similar point. This is easier to see when it is realised that the processes of discovery and of establishing new scientific knowledge (see section 4.7.1 above) generally take some months and often years to be played out. Merton (1961) went further suggesting that any discovery which is a “singleton” is actually a “forestalled multiple” – someone else would have also arrived at the same position more or less contemporaneously.
were it not for the widespread publication of one person’s discovery. His hypothesis was that, rather than the multiple discoveries being the “odd or curious or remarkable”, it is the singletons which require explanation.

Many academics in recent decades have focussed on the social nature of discovery. Referring to the work of Merton, Brannigan (1981) was of the opinion that certain of Merton’s basic concepts can fruitfully be re-interpreted to establish the viability of the idea that discoveries are socially constructed. (op. cit., p. 58)

More recently, Latour and Woolgar (1979) described the social processes involved in a study of how a particular protein was discovered in a specific laboratory.

In the science education setting, there needs to be a recognition and discussion of the various ways in which scientists find new and novel ways of summarising one set of characteristics of nature or of explaining such observations. The preceding discussion indicates a starting point for understanding how this happens.

4.10.3 **The Role of Experimentation**

Experimentation is central to much of the work of a scientist. It includes a range of activities which may involve the use of equipment, which always involves observation, which may involve measurement, which may anticipate a physical product and which may involve deliberate alteration of or interference with natural phenomena by the experimenter. The reasons for undertaking an experimental investigation include the following: the production of new information related to the behaviour of some physical system, the confirmation of such information which has been obtained by others, the determination of the factors which affect particular properties of a physical system, the designing, testing and construction of a piece of apparatus, or the testing of a hypothesis which forms part of or extends a theory describing the behaviour of some natural phenomenon.

Ziman (2000) noted the “complementarity” between theory and experiment:

the whole meaning and purpose of an experimental observation derives from the theoretical context in which it is carried out. (p. 94)

He referred to the “carefully contrived circumstances” required in the design of an experiment so that any results can be attributed to recognisable causes and so that the hypothesis which prompted the experiment can be clearly evaluated. The
deliberate manipulation of the natural world to investigate it has not always been the modus operandi of the scientist or natural philosopher. The paradigm governing the way in which much experimentation is currently performed began to flourish during the seventeenth century. As summarised by Westfall (1977):

it was in the 17th century that the experimental method, the active questioning of nature under conditions defined by the experimenter, as opposed to bare observation of the phenomena that nature spontaneously presents, became a widely employed tool of scientific investigation. (p. 115)

Bacon and Descartes are two prominent examples of natural philosophers at that time who described how nature should be examined (see Chapter 7, section 3.7). Others such as Harvey (the circulation of blood), Newton (the origin of colours) and Boyle (the properties of air) demonstrated their acceptance of such an approach by virtue of their actual investigations.

As Medawar (1996) noted, the role and meaning of experiment has changed over the centuries. The activities described at the beginning of this section indicate what an experimenter might do, but they do not indicate what the experimenter is trying to achieve. The Baconian era heralded a new approach to the way in which natural philosophers interacted with their world, whereas those who performed practical activities during the previous centuries undertook that work in a somewhat different way or for a different purpose. Since the so-called Baconian era, there have been further changes in meanings of experiment, Medawar (1996) suggesting a difference between performing an action to “see what happens … in Bacon’s sense” or seeing if a particular objective could be achieved as “an experiment in the modern sense” (p. 15).

The development of much new instrumentation (for example telescopes, microscopes, thermometers, barometers and clocks) occurred during the seventeenth century when the new experimental philosophy was emerging and this technology development facilitated the adoption of the new philosophy. Henry (1997) suggested that, prior to that time, “the only instruments in use were armillary spheres, astrolabes, quadrants, and one or two other instruments used by astronomers” (p. 24).

During the sixteenth century, experimental work for many natural philosophers could be illustrated by Eamon and Paheau’s (1984) description of what took place in early scientific societies in Italy, particularly the Accademia Segreta
founded by Girolamo Ruscelli. They explained that the notion of an experiment was
different then to what it has become in more recent centuries:

In the sixteenth century, the term “secret” referred, among other things, to an
“experiment”, not in the sense of a test of hypothesis, but rather of a recipe or
formula actually tried out. Thus the aim of the Accademia Segreta … was to “try
out” or “prove” all the recipes and secrets that they could find in manuscripts or
printed books or directly from others. It is important to stress here that Ruscelli saw
this process as a deliberate application of an experimental method. (p. 333)

This secretive aspect of experimentation continued on into the time of Newton
(see Golinski, 1988) and his contemporaries who conducted experimental
investigations in alchemy under the cloak of secrecy as was common for that aspect
of natural philosophy at the time - although Dobbs and Jacob (1995) indicated that
alchemy was not “strictly speaking, a branch of natural philosophy” (p. 21) because it
also involved something of the spiritual as well as the natural.

Eamon and Paheau further emphasised the changing nature and role of
experimentation by pointing to the historical significance of Ruscelli’s work which,
they said, indicated

a stage in the development of the concept of experiment that stands midway
between the medieval concept of experimenta as ordinary experience and Galileo’s
method of using an experiment to test an hypothesis. (op. cit., p. 333)

Elsewhere, Eamon (1994) described the medieval forms of an experiment as
being “a fortuitous, unexpected, and essentially private experience” (p. 9). He
suggested that the books of experimental work which Ruscelli and others wrote
represent a link between the previous secret work and the more public and rationally
based work of Galileo, Bacon and those coming after. The notion of secrets was
almost a paradigm in those earlier years, nature being thought of as containing secrets
which needed to be uncovered. It was incumbent on the ‘scientist’ to retain any
secrets found, partly in imitation of nature’s secrecy, and partly because the scientist’s
work was, to some degree, associated with mysticism and magic, practices which
were frowned on by authorities.

The role of experiments, then, has changed over time. It is important for the
science educator to understand that an experiment has not always been an activity
which is carried out by following the so-called scientific method. There are many
methods of scientific investigation. Although observations of early experimental
work may superficially appear to be similar to current scientific techniques, it is the thought processes directing that observable activity which distinguish one form of experimentation from another.

4.10.4 Replication of Experiments

As far back as the time of Ruscelli and his Accademia, if not earlier, replication of experiments performed by others was and is seen as legitimate activity for scientists. Much of his experimental work involved “proving” experiments and recipes which had been written by others in various manuscripts and elsewhere. They were considered proven or trustworthy if they could be successfully repeated three times. This suggested that it was important not to take for granted whatever was communicated in relation to alchemical and other works. In addition, it implied that replication was not an easy or automatic process and so a number of successful trials were necessary to guarantee the correctness of results.

During the early years of the Royal Society, experimentation was a central activity and was undertaken to ensure that, among other reasons, a single experiment or one performed always by the same person was not a hoax or some other novelty. Eamon (1994) explained that

Replication, it was believed, would make secure experimental facts out of what were commonly perceived as wonders. It would also reinforce the distinction between the true experimental scientist and the dilettante or charlatan. (p. 338)

More recently, Collins (1992) discussed the replication of experiments in order to emphasise the difficulty of that process, particularly given the significance of the underlying theory structure which frames the experimental design. What factors in design and measurement which one practitioner sees as important and, on the other hand, what is not critical to replicating the outcome, is not always apparent to the person attempting to prove the experiment therein reflecting Ruscelli’s use of the term prove. Collins discussed the influence of “experimenter expectancy effects” (p. 30) and the likelihood of them determining whether a replication of a previous result will occur. An appreciation of this is of central importance to science educators who ask students to watch or perform experiments and expect them to observe or reach pre-determined outcomes, either to confirm some physical law or to imitate an earlier scientist’s activity. These goals are two of the most common purposes associated with much secondary school practical work. Dawson (1994) described them but also
discussed their limitations and cautioned against their uncritical acceptance as legitimate aims of laboratory work. There should not be an expectation that certain results of an experiment are necessary or easily obtained, nor that any discrepant result is automatically incorrect. Depending on a range of influences, it has been the case in the past that such situations of discrepant results have been the very source of new and widely accepted observations or theory changes. They should not be portrayed as problematic or wrong, particularly in an educational setting - rather the opposite conclusion should be encouraged, such results providing a basis for further investigation and possible replication.

4.11 The Products of Science

A description of the nature of science requires not only an elaboration of its processes but also of its products. The characteristics of those products are dependent on the same influences as the processes, that is, on the philosophical, sociological and psychological factors discussed in preceding sections.

4.11.1 Observations as Products

The primary products of science are ‘observations’. Such observations are often taken to be ‘facts’ in the sense that what is observed must necessarily be true. Both of these terms are regarded in two different ways within society and within science. On the one hand there is a widespread acceptance of both terms in an objective sense. That is, observations are thought to be essentially clear-cut statements describing what has been seen, and facts are similarly taken to be uncontestable statements which describe observations or conclusions drawn from them. Rennie (2002) referred to the National Academy of Sciences definition of a fact as “an observation that has been repeatedly confirmed and for all practical purposes is accepted as ‘true’” (p. 63). It is presumed that there can be no argument with ‘cold hard facts’.

There is also another view which, while not necessarily implying that there can never be anything which is true or correct, recognises that there are influences which come to bear on statements of observation or fact. The processes by which such statements are arrived at have philosophical, sociological, psychological and cultural dimensions which make those statements open to analysis and subject to qualification. For example, a scientist’s description of what she sees through a
microscope or a telescope may or may not be in full agreement with what another sees, depending on factors such as the training of the second person, the area of interest which each has, the theoretical framework to which each adheres, or on the hypothesis which either might be trying to establish. Hanson (1969) elaborated on such a situation. A layperson with none of this background may not even be able to see a cell nucleus in the microscope or a globular cluster in the telescope. They may describe their view in a completely different way which is not even a recognisable definition of either of these phenomena. Kuhn (1970a) described the incommensurability of observations made by people who operate within different paradigms. Hanson (1969) described similar situations in terms of the ‘theory-dependence’ of observations. Ziman (2000) simply said that “(n)ew ‘facts’ only become visible against old observations” (p. 151).

An understanding of the processes by which statements of observations are arrived at makes it easier to explain and accept change. On the other hand, an unquestioning acceptance of the truth of a statement makes a denial of new observations more likely.

4.11.2 Theories, Laws and Hypotheses

The ‘products of science’ also include the mental structures which result when scientists analyse and interpret the observations they make in an attempt to classify, compare or otherwise organise those observations. Theories, laws and hypotheses are often the end products of these processes. The three terms are sometimes understood to be more or less equivalent, particularly by the wider public in relation to the products of science. On the other hand, the terms are sometimes seen as indicating stages on a continuum which describes the status of a piece of scientific knowledge. A law is seen as being the end result of some previously proposed theory or hypothesis if sufficient supporting evidence is produced. These meanings have some legitimacy in everyday language in a non-scientific context, but they are used in a different sense in science in such a way that the three terms are not directly related. This distinction and these meanings are not often made clear in science education curriculum materials or by science teachers, with the result that students gain a distorted view of science, its processes and its products (McComas, Almazroa and Clough, 1998). For people outside of science, the word ‘theory’ is often used to refer to an untested idea (as in the saying “just a theory”) or as a personal hunch (as in “pet
theory”), and a ‘law’ has the status of something to which natural phenomena must adhere or is a statement of something which has been rigorously proved, while the term ‘hypothesis’ is used to refer to an uneducated guess which is likely to be wrong. There is also an understanding that what begins as an idea, is formulated into an hypothesis which later becomes a theory and may eventually be confirmed as law. McComas, Almazroa and Clough (1998) referred to research by Ryan and Aikenhead who found that many students expressed such a “simplistic hierarchical relationship” (p. 516). Rennie (2002) suggested that people learn that “a theory falls in the middle of a hierarchy of certainty – above a mere hypothesis but below a law” (p. 63).

An interpretation of these terms which is more appropriate to the sense in which they are used in science is required of teachers and students if they are to understand the nature of both the processes and products of science.

A theory refers to a comprehensive and internally consistent description and explanation of a set of related natural phenomena. Hanson (1969) suggested that “(t)heories put phenomena into systems” (p. 90). Rennie (2002) again recalled the National Academy of Sciences for their explanation of a scientific theory as “a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses” (p. 63). The internal consistency may be questionable to some degree around the edges of the theory structure and this may give rise to further research and refining of the theory (the “positive heuristic” referred to by Lakatos, 1970). Examples include a theory of optics, a theory of gravitation and a theory of evolution.

On the other hand a law is a single statement referring to one particular phenomenon and is stated in a way which suggests that a prediction of the outcome of a specific test can be made. Rennie referred to it as “a descriptive generalization about nature”. Consequently we have the law of interference, Newton’s law of universal gravitation or the law of natural selection. Laws relate to one specific aspect of the set of phenomena considered by a theory as suggested by the National Academy of Sciences definition of theory in the previous paragraph.

The third term which is often connected to these first two is ‘hypothesis’. An hypothesis is a statement made about the outcome of an experiment or investigation, and it may be formulated after a number of observations of a phenomenon are made or it may be suggested by the statements which comprise a theory. Medawar (1996)
called it “a declaration with verifiable deductive consequences” (p. 18). But this term too has undergone changes in meaning over the centuries, Medawar recalling meanings from earlier times which included “connotation of the wantonly fanciful” (p. 19) and other interpretations of the concept.

These explanations indicate that there is not a sequence of events leading from hypothesis to theory then to law as understood by students in the Ryan and Aikenhead (1992) research referred to above. Although there is a connection between these three terms, they are epistemologically different and they each have, and had, different roles in their application to natural phenomena.

4.11.3 Models and Analogies

These two concepts are related but different forms of explanation which are used to describe or illustrate a law or theory. Their purpose is to clarify the way in which we understand such laws or theories. They have been considered as different forms of ‘metaphor’ by Leatherdale (1974), while others such as Ziman (1978) have been inclined to consider them almost synonymously: “(a model) is no more than an analogy or a metaphor” (p. 23). Ziman (2000) shied away from defining a model - “the notion of a model defies formal definition” (p. 147).

A model may be a qualitative description or it may be expressed quantitatively in mathematical form using equations or graphs. Essentially it draws a number of parallels between the phenomena to be explained and some more familiar situation. The effectiveness of a model is related to the degree to which it can clarify a range of phenomena; direct equivalence between the model and the concepts it illustrates is not a requirement. It may be, as Ziman (2000) observed, that a “ready-made model can be taken over from another branch of science … (or it may) come straight out of everyday life” (p. 149). It can be literally physical, for example a scale model of the solar system, or it may be a description of a physical situation, for example the particle model of a gas. Ziman recognised that a model is such an important adjunct to a theory that the two terms are often taken to be synonymous. It is important to understand, however, that there is a difference between the two - although light and waves have many common properties, light is not a wave even though waves can be usefully employed to further an understanding of light and to describe it more clearly.
Where there may be a difference between model and analogy, the latter is a less formal concept than the former. A model aims to be a comprehensive description of a set of related phenomena and uses familiar physical realities or mental constructs to illustrate unfamiliar phenomena and to enable predictions to be made based on it. Analogies, on the other hand, compare one set of circumstances with another taken from a different context in a much more limited set of situations and without expecting to withstand rigorous challenge as to the extent of the parallels drawn between the analogy and the phenomenon it elucidates. For example, Descartes referred to the blind man’s cane as a means of conveying his understanding of the way light was propagated.

4.12 Science, Scientific Knowledge and the Individual

The processes of science and their relationship to those people conducting scientific work was discussed from the sociological standpoint in sections 4.9 and 4.10 above. There is a suggestion that there is a certain inevitability about the scientific knowledge which is produced, at least that could be a possible interpretation of those referred to in section 4.10.2 above on discovery processes. One could arrive at such a view from arguments surrounding the occurrences of multiple discovery, particularly by those whose view is that multiples are the norm. In a given scientific climate where there is widespread interest in certain phenomena, when one scientist (or group) reaches a certain point it is highly likely that others will do so soon also.

While there certainly have been many instances of multiples, that should not detract from an analysis of the processes and products of science which recognise the more esoteric qualities which convey the human dimension of scientific work. The creativity and insight displayed in the process of a particular scientific work, or the beauty and simplicity underlying the synthesis of observations and explanations into a coherent theory are all given due recognition in various forums within science and even in the wider society. These are the factors which are often deemed significant in the formal rewards and awards which are conferred on scientists, perhaps more so within science as scientists are likely to be those who most readily perceive and understand the aesthetic qualities required to produce a particular outcome.
4.13 Conclusion

The preceding chapter has merely scanned the surface of the characteristics of science, but no more than that was proposed at the outset. This research was not intended to be a comprehensive analysis of science. As explained in the introductory section of this chapter, it is important for those associated with science education to have some understanding of the ways in which the processes and products of science might be described, and what the influences on their actual outcome might be.

Literature commentaries often focus on one aspect or another of the nature of science. This thesis includes, as part of the curriculum design framework of Chapter 6, a framework for analysis of the characteristics of science based on a view of science as a society – a notion which has been described in section 4.8 of this chapter.

Throughout this chapter many characteristics of science have been highlighted although there has been scant demonstration of such characteristics in actual practice in order to verify the existence of such qualities. This is where a study of the history of science becomes fundamental, particularly for science students in secondary education where descriptions of such generalities have little impact without illustration. The essential and central nature of the history of science to an appreciation of the nature of science and ultimately to the achievement of scientific literacy is demonstrated more fully in Chapter 5.

Prior to that development, however, the chapter which follows establishes a clear connection between the goals of scientific literacy on the one hand, and the history of science and the nature of science on the other.

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CHAPTER 5

SCIENTIFIC LITERACY AND THE HISTORICAL APPROACH

5.1 Introduction

In Chapter 3, the meanings of the term ‘scientific literacy’ were examined over the period of time from the late 1950s to the late 1990s. Changes in understanding of the concept were apparent and there was a significant increase in the range of related approaches and emphases in the more recent years. The frequent occurrence of the need for an appreciation of the nature of science was noted and, accordingly, that concept was analysed in Chapter 4 in some detail to uncover what may need to be understood in the quest for scientific literacy.

The aim of this chapter is to clarify the necessity for an appreciation of the nature of science as a requirement for the attainment of scientific literacy, and to argue that the former cannot be achieved without the adoption of a historical approach. This discussion will also allude to the paucity of arguments proposed, in the recent and more distant past, in relation to that connection. In essence, a further step in both the scientific literacy and historical approach debates is to consciously and of necessity draw the two together in such a way as to propose that the former cannot occur without the latter, and that the path from one to the other includes an appreciation of the nature of science.

The first part of this chapter is concerned with an examination of the courses and approaches which have a historical focus and which have been put forward by the educators and commentators introduced in Chapter 2. A lack of purpose in these arguments will be noted with respect to the attainment of scientific literacy as a goal of science education. The latter part of the chapter is devoted to establishing an essential link between the range of aims of scientific literacy and a historical approach.
5.2 **The Purpose Of Historical Approaches**

5.2.1 **General Literature Contributions**

The arguments in favour of a historical approach to science curriculum described in Chapter 2 can be related to one or more of the following purposes with respect to the use of history:

as a purely historical study;

as a means of generating conceptual understanding;

as a vehicle whereby science can be encountered in a ‘liberal education’ course.

The last of these is the only one which, on its own, appears to be heading in a scientific literacy direction. However, the meaning of the *liberal education* term is not clearly defined by many of those contributors, other than recognizing that it is usually applied to courses for ‘non-science majors’. In other words, the vast majority of the arguments proposed for historically-based courses do not intentionally address the scientific literacy goals which are put forward elsewhere as the requirements for science curricula.

5.2.2 **Specific Contributors**

In this section, the purposes for a historical approach which were outlined by the five significant contributors of Chapter 2 are reviewed. Again, with the exception of Matthews’ ideas, there is little commonality between their intentions and those of the scientific literacy theme.

51.2.2.1 **Mach**

Mach’s view of using history in science touched on each of the three categories in section 5.2.1 above, but may best be considered primarily as a combination of the first and second of those purposes - he had proposed that students study the work of a relatively few eminent scientists, but not simply for conceptual understanding of a particular piece of scientific theory. His goal was more concerned with the appreciation and acquisition of a rational, intellectual thought process by examining those characteristics as exhibited in the work of scientists such as Galileo, Newton and others. (see ‘On Instruction in the Classics and the Mathematico-Sciences’ in his *Popular Scientific Lectures*, Mach, 1893/1986). He argued for this in
the broader context of encouraging a liberal education, while admitting that such an
education could only begin to be acquired during school years.

While Mach’s views have been significant in any review of approaches to
science education over the last hundred years, they obviously related to a different
educational era. At that time, a full six years of secondary education was very much
the exception rather than the norm, and such education was concerned primarily with
a study of the classics and the arts. It is within this framework that Mach’s proposals
were developed and so it would not be expected that his ideas would link too closely
with recent notions of scientific literacy. Nevertheless, the broad tenor of his
approach to science education is in sympathy with some aspects of current ideas.

51.2.2.2 Conant

Conant’s primary goal was to provide an understanding of science for those
(undertaking tertiary studies) who would not be making a career in science. His
approach was therefore related to the third of the above three styles - the liberal
education focus. History was clearly central to all of Conant’s teaching. His view was
that people needed to understand the nature and limitations of science, rather than any
piece of conceptual or factual knowledge. While some encounter with such
knowledge was inevitable in delving into what science is, that knowledge was neither
the focus nor the goal of Conant’s science education. He recognized that there was a
social dimension in defining the processes and outcomes of science. As might be
expected on the basis of their academic associations, there are elements of Kuhn’s
(1970) description of scientific development in the themes which are reminiscent of
Conant’s ideas and are ones which he regards as significant and central in his
explanation of how science ‘works’. Among the less traditional of these themes are
Conant’s (1951) proposals that

New concepts may result from accidental discoveries which are followed up ……
New concepts may evolve through a series of successive approximations from older
ones, the modification never being so drastic as to constitute a complete jettisoning
of the older idea ……
A new concept may be revolutionary and after its formulation a host of old facts
may be fitted into the new scheme and many new facts discovered ……
A scientific discovery must fit the times ……
A well-established concept may prove a barrier to the acceptance of a new one ……
Old concepts may be retained in spite of alleged facts to the contrary ……
Erroneous observations or interpretations of experiments frequently persist and confuse the development of new concepts .... (p. 105-107)

These ideas illustrate that Conant was certainly interested in the way in which the scientific enterprise is undertaken, and not just from the ‘standard’ viewpoint. In addition to any connections between Conant’s and Kuhn’s ideas, the former also appears to be an early form of the discourse later known as the social construction of scientific knowledge which was put forward by the so-called Edinburgh School during the late 1970s (see chapter 4, section 4.6.3). Despite this, Conant’s science education missed many of the features of the current understanding of scientific literacy which have been described in Chapter 3, and, in any case, was not based on a Science for All or Scientific Literacy platform. In addition, his work was directed only at university students as distinct from the secondary school student group who are the focus of the scientific literacy debate.

51.2.2.3 Holton

In the late 1960s, Holton (and his colleagues) developed the Harvard Project Physics Course (PPC) for students in their senior years of secondary school. This was the first clear attempt to actually design and implement a science course which recognized the history of science in secondary education. The basis for that course was the view that potential scientist and non-scientist alike should be aware of the nature of science and its essentially human origins. Holton’s approach predated that of the Science For All movement in the 1980s in that it was not aimed solely at students intending to proceed to tertiary science studies. Where he differed from the Science For All approach was that his course was designed for the ‘elective’ years of senior secondary education and so was still unable to reach all students as the Science For All notion implies. Some of those associated with the development of PPC saw it primarily as a means of addressing an enrolment decline in the sciences at the senior end of secondary school. In his discussion of factors which prompted the beginnings of the PPC, Holton (1978) observed that

scientists and officials were concerned that the proportion of students in the United States taking any introductory course in physics, alone among all the sciences, was continuing to decrease.

For Holton (1978) himself, however, the purpose of the PPC was
to provide a model both of a style of going about making a curriculum development... and of an approach to the subject matter. The latter - a humanistic conception of science - is really at the heart of the program. (p.289)

And further,

we wanted to illustrate how physical science actually developed as well as the humanistic and societal impact of science.... those aspects which are particularly meaningful to students in the large middle group of our audience (p.295)

Sometime after developing his PPC course, and in an unrelated paper, Holton (1975) outlined the reasons why an educated person should know some science. He referred to cultural background, career opportunities, intelligent citizenry, and personal “sanity”. The breadth of these ideas is beginning to stretch beyond the three points mentioned earlier, and perhaps his use of the term ‘educated person’, like the ‘liberal education’ notion, represents the beginning of a realization that science involves much more than the acquisition of conceptual knowledge - a realization which is dealt with more explicitly in the scientific literacy debate.

The PPC was a science course which incorporated history much more than any other, but it still fell short of addressing the fuller meanings of scientific literacy as described by many during the 1980s and 1990s, and as outlined in Chapter 3. Nevertheless, the course cannot be criticized for that, because such notions had not been enunciated at that time. When it was published, the Harvard course was a significant advance in science curriculum development.

Although it was an advance on other science courses available at the time, it was still a course as distinct from a curriculum development framework. It provided a detailed set of resources for classroom activity. This thesis involves that earlier stage of development which considers what should be taught, for what reasons and how a course should be constructed; having undertaken such a process, something like the PPC may be one result of such a curriculum design plan. If any criticism is offered with respect to that course, it may be that there does not appear to have been any conscious analysis undertaken to determine what were the characteristics of science which the PPC was intended to highlight. To that extent, these characteristics and the nature of science which they were intended to illustrate were encountered somewhat incidentally throughout the course as part of the discussion of some particular scientific development. To address such criticism by including in such a program a
more formal examination of the nature of science may be expecting more in a physics course than is reasonable, and may result in it being less recognizable as a science course and more as philosophy and sociology of science. But even if such explicit considerations of philosophy and sociology of science are not presented to students within course itself, teachers still need to be aware that the course has such an analysis as an underlying theme. To that extent, teachers need to be familiar with a more formal examination of the nature of science. Perhaps that may have occurred in the teacher-training sessions held in conjunction with the introduction of the PPC but any such structure is not apparent in the printed materials which formed part of the package which teachers would have worked with if they adopted the PPC without access to any implementation training.

The other difference between Holton’s PPC and an approach which addresses the concepts of scientific literacy is the lack of an explicit social responsibility consideration. In the PPC, there were connections made, at appropriate stages, to the links between science and the society external to science. However these connections tended to be somewhat clinical in their analysis and there certainly was no conscious attempt to develop in students a socially responsible bias in their investigation of any particular stage of scientific development. Put another way, the PPC encouraged an understanding of the human characteristics of others who contributed to scientific development, but did not present students with an opportunity to make their own contribution to and consideration of the worth of earlier or more recent scientific developments. Holton (1978) proposed that it was

   essential that students see the full vision of science and thereby be protected from the narrow blinkers or naive euphoria just as much as from the false and hostile ideas about science and scientists which have been spreading in the past three decades. (p. 290).

The end result was that there was no purpose or outcome expected of the course beyond the study of a physics text itself, albeit one which presented a significantly different emphasis from other contemporary courses. What was still required was the framework within which course designers and teachers could construct a science curriculum for themselves based on a clear understanding of the purposes of such a course, without having to rely on using an already packaged product.
51.2.2.4 Brush

Brush’s encouragement to use history in the teaching of physics was related to the need that he saw to present, in clearer perspective, the way in which scientific ideas develop. He suggested that there needed to be a change in the way that it is done compared to the approach which had traditionally been presented in texts and courses which referred in some way to history. This latter often misrepresented the true picture in an attempt to show the logical development and interconnections of scientific concepts. He recognized the importance of the humanistic view in any examination of the development of ideas. Brush naturally approved of the PPC approach to physics teaching, having contributed to its development. His reasons for advocating history of science in science teaching essentially related to the value of history itself and what it can show about the nature of science. Brush (1969) suggested that “(t)he goal of (a college science) course would be to discover how science really works by examining actual discoveries” (p.279). To be sure, this is one aspect of scientific literacy, but Brush did not have scientific literacy as a framework guiding the formulation of his curriculum approach which was focussed predominantly on the first of the three points mentioned earlier in section 5.2.

Even more than Holton, Brush’s approach was primarily an internal one, looking at science from within, with little emphasis on the connections between science and the wider society.

51.2.2.5 Matthews

Matthews’ ideas of history of science in science education represent a further development, beyond Holton’s PPC, towards a 1990’s understanding of scientific literacy. He specifically made reference to the scientific literacy notion (for example, in Matthews (1989), (1994) and (2000)) and the connection which exists between that concept and the history and philosophy of science. The present thesis will go further than that, however, in arguing not just for the existence of common features but of essential connections between the two notions - connections without which scientific literacy cannot be achieved.

There is also a difference in the type of contribution made by Matthews compared with that of Holton, in that the PPC stood out as an actual secondary school course, while Matthews has argued in general about historical approaches to science education. He has provided detailed examples to illustrate his point, such as
Matthews (2000) in which he focused on the history of pendulum motion as providing a path towards scientific literacy. He also gave due recognition to the PPC. For example, in Matthews (1989) he observed that

Harvard Project Physics has been an exemplar of what the history of science can contribute to the development of science curricula. The success of the course is encouraging .... (p. 6).

and in Matthews (1990) he also commented on that course:

Its success in retaining students, involving women in science courses, developing positive attitudes towards science, developing critical reasoning skills, and raising scores on attainment tests, has provided evidence for the inclusion of HPS in contemporary curriculum developments. (p. 221)

Matthews did admit an “essential” imperative in relation to the history and science education but it was primarily directed towards “teachers’ familiarity with the history and philosophy of science” (p.28, my emphasis). This echoed his earlier (1988) view that “(t)he benefits of science teachers having an interest and competence in the history and philosophy of science are apparent” (p.74). To be sure, that is an important first step in relation to HPS in the science curriculum, but this thesis will argue further that history is an essential part of science curricula designed for secondary students if the current conception of scientific literacy is to be achieved. Throughout his writings (especially Matthews (1989) and (1994)), he has detailed the benefits which come from an historically based science course, without arguing its necessity.

Matthews’ (1994) central belief - “that science teaching can be improved if it is infused with the historical and philosophical dimensions of science” (p. xiii) - appears to place less of an imperative on the history of science than will be argued later in this chapter. He refers to two ways of involving history in science courses: “the ‘add-on’ approach ... (and) the integrated approach” (p.70). The first approach is dismissed as being of little real value, and the second is described as history being “integrated into the study of science content” (p.70). It is the contention of this thesis that the reverse should be the case - that is, that the science content should be integrated into (or, better still, logically arise from) the historical analysis.
5.3 **Review of Calls for an Historical Approach**

Each of these contributors has directed their arguments primarily at the need for incorporating history of science into the teaching of science, or, more strongly, basing a science course on the history of science. However there has been no requirement for such an approach as a precursor to the attainment of scientific literacy, although Matthews (2000) has at least recognised the connection.

It is significant that the general consistency of proposals over a period of time to adopt a historical approach do not match the degree of their implementation. This suggests that the task of adopting a historical approach is difficult and begs the question of whence that reluctance (or outright opposition) to incorporating such an approach arises. Possible answers could point to the difficulty of teaching such a course, the lack of training of teachers in such an area, the reluctance of universities and teacher-training institutions to consider such an approach, pressure from industry to ensure that the educational focus of science courses is only on concept development, or the pressure from and philosophy of governments whose positivist or uninformed views of science result in the designing of narrowly-focussed curricula. The answer to this question could form the basis of a study of the influences on science curriculum development. A related study has actually been undertaken by Hart (2001) who described and analysed her personal experiences as a member of a committee established to redesign the senior school physics curriculum in Victoria and these confirmed the existence of a range of pressures which constrained any new developments to fit the demands of various groups such as those referred to above.

5.4 **History in the Broader Sense**

While the focus of this thesis is on the development of a particular approach to science education (one which derives from current conceptions of scientific literacy and which is centred on an historical approach), its philosophy emanates from a broader view of education itself. Beliefs about an approach to science education are subservient to, and reflective of, beliefs in the importance of science education itself. These latter are, in turn, predicated on views of the function of education generally. Although a comprehensive analysis of the functions of education in a society is beyond the scope of this thesis, it is important to note the connections which others have made between education, culture and history.
Education is broadly directed towards students gaining an understanding of themselves as individuals, and of their relationships with others and with the material world. Matters related to the spiritual world are also an important, even primary, feature of some forms of education, and in some societies. Ultimately, education is concerned with creating an awareness of, and the adoption of, a ‘culture’: a set of characteristics and habits of a group of people, and the way in which they view and interact with their world. This conceptual interdependence between education, culture and society has been developed by Williams (1961), and later by Billington, Strawbridge, Greensides and Fitzsimons. (1991) (who drew heavily on the former, in particular). Williams (p. 125) considered that

(i)t is not only that the way in which education is organized can be seen to express, consciously and unconsciously, the wider organization of a culture and society, so that what has been thought of as simple distribution is in fact an active shaping to particular social ends. It is also that the content of education, which is subject to great historical variation, again expresses, again consciously and unconsciously, certain basic elements in the culture, what is thought of as ‘an education’ being in fact a particular selection, a particular set of emphases and omissions.

Billington (p. 139) expressed it more succinctly:

Education is a major transmitter of culture and from Matthew Arnold to F.R. Leavis, debates about English or British culture have been in part, debates about education.

Whitehead (1962/1929) was another who saw the focus of education as being related to culture. In his *Aims of Education* he stated that

(what we should aim at producing is men who possess both culture and expert knowledge in some special direction. …. The general culture is designed to foster an activity of mind; the specialist course utilizes this activity. (p. 1).

Culture only has meaning if it incorporates a study of the *history* of at least one culture. Because it concerns changing characteristics over a period of time, it is the history which will demonstrate what is the *culture* of the society. It will show what the society owns. In the absence of any historical rationale, the habits and beliefs which grow and evolve within a society would be indistinguishable from unilaterally imposed behaviours. The acceptance of the notion that societal habits, beliefs and viewpoints are culturally based will occur if it can be demonstrated that different characteristics can be recognized in different cultures. Ideally then, more
than one culture would be studied. Culture with history conveys meaning, purpose and significance. Culture without history, if there can be such a thing, becomes axiomatic dogmatism - actions, views and beliefs are done or held because they are the ‘rule’. The former situation is democratic and liberating; the latter is authoritarian and dictatorial. The former is truly education; the latter is closer to indoctrination. Thus history is connected not only to science education but is taken to be essential to education itself if a culture of the society is to continue.

So the education which young people gain at school is intended to give them some appreciation of the customs of their society. In western societies, these generally translate into subjects as varied as the primary language of the local community (e.g. English), social studies, art, commerce, home economics, politics, and physical education. Students also gain some understanding of how the world is perceived and how their society interacts with it. This occurs in other subjects such as the crafts, technology, geography, mathematics and science. If all of this is undertaken in the absence of history, then what is taught to students is no more than a plethora of more or less arbitrarily devised rules and procedures. Whitehead (1962/1929) referred to them variously as “intellectual minuets” (p. 32), and

A rapid table of contents which a deity might run over in his mind while he was thinking of creating a world, and had not yet determined how to put it together. (p. 30)

His derisory dismissal of subjects taught in isolation came after expressing a more positive point of view in which he argued for the eradication of

the fatal disconnection of subjects which kills the vitality of our modern curriculum.
There is only one subject-matter for education, and that is Life in all its manifestations. (p. 30)

He also indicated the thread which might link the separate subjects into a coherent whole. Whitehead's view was that education should focus on utility for the student in the present, not the future, and he suggested that the content of individual subjects would be seen as having some purpose if they were seen as a “means of studying the world”. In discussing the utility of Algebra, Whitehead observed that

(s)ome of the simplest applications will be found in the quantities which occur in the simplest study of society. The curves of history are more vivid and more informing than the dry catalogues of names and dates which comprise the greater part of that arid school study. … the route from Chaucer to the Black Death, from
the Black Death to modern Labour troubles, will connect the tales of the medieval pilgrims with the abstract science of algebra, both yielding diverse aspects of that single theme, Life … (p.31-32)

An understanding of history gives some explanation and rationale as to why a society and its individuals behave, understand and interact in the ways described in the various subjects taught at school. History provides the link between those subjects. The reason why a society has the characteristics it currently possesses is because of the characteristics it previously had. So an understanding of history also provides the opportunity for society to learn about itself.

In this very broad sense, then, history is the foundation stone of education. No awareness of history means no liberal education, no scientific literacy and no culture, just obedience. But this is not to suggest that all subjects must develop, necessarily, out of a historical study, or that science should only be a study of the history of the interaction between a society and the world it sees. It is important, however, that the science that is offered to students is seen to be derived from, dependent on and characterized by what has happened before.

5.5 Establishing the Connection

There are two aspects to the debate surrounding the adoption of an historical approach in science courses. The first is to argue its necessity and the second is to propose the means by which it is achieved in terms of curriculum design. The first of these points will be addressed throughout the rest of this chapter, and the second will be central to Chapters 6 and 8. The analysis in Chapter 3 highlighted the pervasiveness of the ‘nature of science’ in the spectrum of definitions of scientific literacy. While different educationists may refer to various other factors in their understanding of the term, they invariably include the nature of science as one of its components. This indicates that an appreciation of the nature of science is an essential precursor to the attainment of scientific literacy, irrespective of the possibility that other features of a science curriculum may also be required. The following sections elaborate on the necessity for a study of scientific history as the framework for developing an understanding of the nature of science.
5.5.1 The Characteristics of Science

In Chapter 4 there was detailed analysis of some of the many facets of science and the ways in which it can be analysed and interpreted. The importance of gaining an awareness of what science is and means, and how it is undertaken and developed are recognised by the inclusion of those notions in the central concepts of scientific literacy as discussed in the chapter 3. In elaborating on that theme, various contributors have used phrases such as ...

“science ... and technology are human enterprises” (AAAS)

“science as a human construction” (Arons)

“science as it happens in practice” (Shortland)

“historical origins” (Shortland)

“human origins” (Atkin and Helms)

“appreciate scientific processes” (Atkin and Helms)

If a student is to become scientifically literate, there needs to be more given to the student than mere statements of these characteristics. Making a general statement about a particular characteristic of science or way in which scientific activity can be viewed requires also the presentation of the evidence which supports that statement. In other less well-informed contexts (films, books and the general public perception), the student is all too often presented with images of science which do not accord with those referred to above. If other characteristics, ones which may provide more accurate pictures of science, are merely described without presenting appropriate images of them, students’ initial perceptions are unlikely to be altered. These descriptions of the nature of science need to be developed out of a study of a historical episode or a related series of them. It should not be approached by first describing a characteristic and then demonstrating it with a historical illustration. This is akin to studying the conclusions before actually reading the story, and only referring to the story where evidence is required to support one of the conclusions without ever having read the story itself. It is an approach which calls to mind the “rhetoric of conclusions” comment with which Schwab (1964) condemned the science curricula which promulgated value-free views of science in the 1960s.
Students need to study the story which illustrates the features which science is purported to display for a number of reasons. One significant reason concerns the non-science students and the lack of contact which they will have had with the institution of science and its practices. With no direct experience of the way science operates and how scientific knowledge develops, such students will have little understanding of these things if they are merely told what the characteristics of science are – they need to have read the stories and not just be given the conclusions. There is also a strong argument for science majors to have studied the nature of science through its history. To appreciate the role they will play within science it is essential for them to understand that enterprise – there will be little opportunity for such reflection once they are immersed in it.

Another reason for studying specific historical situations relates to the stage of cognitive development which pertains to secondary school years: students need to be given specific instances and examples to challenge existing schema and to assist in the “assimilation” and “accommodation” processes described by Piaget (Flavell, 1963). In other words, the actual stories of what happens provide the concrete illustrations which are required for students to develop their understanding of what constitutes science. Presentation of the more abstract set of characteristics, without the stories, as the only means to enhance students’ appreciation of the nature of science runs counter to Piaget’s analysis of the age-related processes of cognition.

Thirdly, an awareness of the events in science must precede any subsequent discussion of their general characteristics. If the nature of science is accepted as a significant component of scientific literacy then a study of that nature needs to be based on careful observation in the spirit of Bacon to avoid the feigning of hypotheses as Newton claimed to avoid.

And fourthly, these characteristics of science are not independent entities themselves - they arise from the events which take place when scientific activity is undertaken. The argument here is that it is not sufficient to suggest that examining particular historical examples is a good way of illustrating the characteristics of science. The case is much stronger than that - without the historical examples, there is no nature of science. Without studying the bent stick in a glass of water, there is no refraction.
5.5.2 **External Connections and Responsibilities**

Another of the current conceptions of scientific literacy which rely on history is the External Connections and Responsibilities theme. Relationships and influences between the three spheres often referred to as Science, Technology and Society have been a focus for study since at least the 1930s after comment and analysis by people such as Bernal (1939) and Rose and Rose (1969). As discussed in Chapter 3 (section 3.4.4), ‘Science, Technology and Society’ (STS) became an educational theme in the late 1970s, one of the first to suggest such an approach being Ziman (1980). That the history of science is integral to any STS studies is almost as significant as it was in the Characteristics of Science case in the previous section: the value of a study of the interrelationships of science, technology and society is clarified and emphasised if particular instances which demonstrate such connections are studied. A study of the inter-relationships of science, technology and society only has meaning in the context of particular instances which demonstrate such connections. Arons (1983) recognised this by explicitly including case studies of the inter-relationships between science, technology and society as a component of his conception of scientific literacy.

A somewhat separate but overlapping curriculum theme has been the Social Responsibility in Science movement, highlighted in recent times by Jenkins (1992 and 1994), the American Association for the Advancement of Science (1989 and 1993) and Cross (1990). Earlier, the National Science Board (1983) in its Commission on Precollege Education recognized the importance of civic responsibility, options for action, consequences of actions and importance of action. The Social Responsibility in Science aspect of scientific literacy also relies heavily on history in science education. Although the main focus of that movement is the development of such a responsibility in students, the importance of its acquisition can be illustrated to students by examining historical cases (in the recent past or longer ago) in which such responsibility was or was not demonstrated, and noting the consequences which resulted from the application or otherwise of a social responsibility. In addition, studies of such historical events can provide students with examples of methods by which social responsibility in science-related community issues can be demonstrated.
5.5.3 Personal Involvement in the Scientific Process

The current conceptions of scientific literacy described in Chapter 3 also include an area which could be described as Personal Involvement in the Scientific Process. One of the clearest examples of this notion was proposed by Roberts (1983). Among his seven curriculum emphases was one which he referred to as ‘Self as Explainer’. This title does not directly suggest a study of the history of science per se, because the focus of the term is on the student learner. That focus could become indistinguishable from a ‘classroom learning technique’ if there was no historical discussion. That is, encouraging students to be actively involved in offering their own suggestions, ideas and interpretations of observations and of secondary data could be used by the teacher as part of a constructivist approach to teaching and learning. However the ‘Self as Explainer’ approach has a greater benefit than that: it requires an examination of the way in which scientists have produced the science of their time (be that relatively recently or longer ago), by encouraging students to offer something of their own thoughts on their investigations or on the observations of scientists from the past, and so reflecting the actions of scientists themselves. This will be seen by the students as participating in their own form of scientific investigation if they have seen the role which scientists have played in the formulation of science in the past. But this latter component is an essential requirement if students are to compare and contrast their own ‘scientific’ approach with that of actual scientists. They cannot infer characteristics of science solely from their own attempts to act as scientists. The human and personal dimension of science shows the student that science is much more than practical, observational and measurement skills; and more than (or not even) an objective set of textbook dogma. The mental challenge which ‘Self as Explainer’ suggests is the same challenge which scientists have wrestled with throughout the ages. A realization of this can only come with a study of the history of science.

Arons (1983) included an ‘appreciation of the scientific and personal world view’ and ‘science as a human construction’ as components of scientific literacy. An awareness of how science has developed, of the way people have contributed to that development and of who those people were are all essential in gaining the appreciation which Arons recommended. His view, in effect, was that the actual history of science needs to be studied, not only as the platform on which aspects of
scientific literacy might be constructed, but as a specific component of science courses in its own right.

Ten years after Arons, Atkin and Helms (1993) saw the relationships between science and human thought as a component of scientific literacy, and that there should be an emphasis on the intellectual and social history of the subject. As was the case with Arons’ ideas, this view of Atkin and Helms conveys a clear necessity for the inclusion of history of science on its own merits, apart from any other benefits which such an approach might bring.

5.6 Conclusion

This chapter began by looking at the views expressed by a range of contributors with respect to the adoption of an historical approach to science education. It was observed that these were centred on the use of an historical approach per se - no reference was made to scientific literacy. In section 5.4, reference was made to the broad view of education, in a liberal sense, with the notion of a societal culture, and the centrality and significance which history has in all of that. The final section examined some of the facets of current conceptions of scientific literacy, particularly the nature of science component, and indicated that there was a requirement for a study of scientific history in every instance. In essence, the argument is summarised as follows. Irrespective of the contributory source, an understanding of scientific literacy always refers to the importance of the nature of science, and an understanding of the latter cannot be properly addressed without first having examined scientific history.

The following chapter proposes a curriculum design framework which is based on a study of the history of science.

51.6.1.1 REFERENCES

American Association for the Advancement of Science (1989), Science for All Americans, Oxford University Press, New York.


CHAPTER
6

THE HISTORY OF OPTICS

6.1 Introduction

Discussion in earlier chapters (especially Chapter 2) demonstrated the widespread support which has existed over many years for the inclusion of an appreciation of the history of science in science courses at secondary school. Particular characteristics of science which are important in developing this appreciation were outlined in Chapter 4, and the linking of these to the concept of science literacy has been discussed in Chapters 3 and 5. A general framework for the development of an appropriate science curriculum has been proposed in Chapter 6. The present chapter and the one following focus on how this framework could be applied to a particular field of study in science: Optics. The historical analysis covers developments in our understanding of light since about 1600. The examination of that history is undertaken on the basis of the characteristics of science, which were outlined in Chapter 4. In Chapter 8 this analysis will be organised into a framework based on the nine ‘systems’ of a society described by Lawton (Chapter 6, section 6.5) to provide an example of curriculum planning within a particular science topic. The analysis of this chapter is therefore not a summarised set of events organised chronologically from the beginning of the sixteenth century. Rather, it examines the history of optics as viewed from a range of themes and episodes in a way which could be replicated in any field within science. Instances are chosen from optics so that, not only are the main events in the development of optical theories encountered, but also there is some examination of the ‘how’ and ‘why’ of the theory development. It is not the purpose of this thesis to provide complete detail of that history - this can be found in many sources (including those listed in the bibliography of this chapter). The purpose of this analysis is to refer to situations which illustrate particular characteristics of science and to indicate where those events and their interpretations are described more fully in the literature. The scope of this analysis includes the philosophical and scientific significance of the speed of light and of the ether, Newtonian dominance especially in the eighteenth century, the use of analogies, laws and models in the development of theories, multiple discovery, the ways in which theories change, and a description of the many versions of theories of light.
With respect to physics education at the secondary school level, the depth of content in this chapter and the analysis undertaken are greater than would be expected of most students, but the approach indicates the appreciation of science which teachers should have developed if they are to provide appropriate direction to students’ studies. No attempt is made here to specify what might be the limit of content which students should encounter - it is appropriate that this will always be something determined by the teacher who is in the best position to judge the interest and capabilities of the class.

6.2 Approaches to Historical Study

Hindsight and Reconstruction versus Empathy and Reality

It is widely believed that the historical, social and cultural constraints within which a scientist works occur primarily within, and associated with, the institution and culture of science itself, but there are also external societal influences and modes of thought which have been just as powerful in determining what scientists did and how they thought. If these issues are neglected in a study of the history of science, it is likely that the resultant historical understanding will be superficial. The history is reduced to just a recollection of events (Brush’s views were consistent with this approach and were discussed in section 2.3.4). This is often the case with the way history is incorporated into many standard texts and courses aimed at the secondary school level. They contain references to historical developments or people which are anecdotal, episodic, marginal (often literally so) and lacking in significance in terms of the central focus of the chapter or textbook. Matthews (1994) expressed concern and regret about the all-too-often total lack of reference to history in many school and college physics texts and courses and elaborated on some of these in a chapter entitled “History of Science in the Curriculum”.

In cases where school textbooks do attempt to include some historical information, a common trait has been to describe history from the standpoint of today’s thinking and today’s paradigms. A frequent illustration of this is the way in which the work of Thomas Young is dealt with. In some standard texts, Young is referred to as the person who proposed, initiated or proved the idea that light was a wave (for example Resnick & Halliday (1966), Haber-Schaim, Dodge and Walter (1971), and Storen and Martine (1987)). At best, this can only be stated with the benefit of hindsight, and even then is at odds with much of what Young himself
admitted. Because interference is a wave phenomenon and does not occur in any way with particle beams, and because a similar effect was seen to occur with light, a logical interpretation would be to describe light as a wave. However such a logical reconstruction of events does not describe what actually happened in the early years of the nineteenth century and does not give credit to the significant contribution to the debate made by Fresnel. While Young did rekindle the wave-particle debate in the early 1800s, it could hardly be said that he proposed or developed a wave theory of light. As Cantor (1983) has pointed out, as late as 1817

(Young) claimed that the available hypotheses about the nature of light were only ‘temporary expedients for assisting the memory and judgment’ by connecting the facts together. (p. 134)

And, further on, Cantor concluded that

(Young) appears in his writings to have distinguished between the law of interference and the hypothesis of vibrations. (p. 140, Cantor’s emphasis).

Young was less interested in developing a general theory of light than he was in explaining interference and, in any case, his broader interest was in developing a theory of the ether rather than a theory of optics.

Texts similar to those referred to above also convey an oversimplified view of science, an example being the way they deal with the particle-wave dichotomy as a description of light. The student using such texts could be excused for thinking that everyone prior to the early 1800s thought that light was a particle and, soon after Young, that light was a wave. Again this does not accurately represent the situation in which there were numerous forms of a particle theory, other theories which were not really particle theories at all, and many people during the 1700s who found significant problems with particle theories and provided arguments in favour of a wave theory. Further details of these issues are covered later in section 7.5.2.

The examples just discussed illustrate that important details are omitted and incorrect impressions are conveyed by the way many common texts cover the historical aspects of a particular field of science. The events which led to the current state of knowledge are the only ones which are examined and linked, one after another, so that only the trail which leads from past to present can be mapped - the past is not studied for its own intrinsic value. Such an approach also tends to highlight the imperfections in earlier thinking vis-à-vis the present. There is an assumption that
scientists in past eras were attempting to reach the present viewpoint but had been unable to see the way. The approach tends to be a comparison between what was known then and what is known now, rather than a study of what was known then for its own sake. Butterfield (1963) referred to the former approach as “Whiggish” and held it to be inappropriate and misleading, at best:

The whig historian stands on the summit of the twentieth century, and organises his scheme of history from the point of view of his own day … He can say the events take on their due proportions when observed through the lapse of time. (p.13)

and,

an alternative line of assumption … [occurs when] he comes to his labours conscious of the fact that he is trying to understand the past for the sake of the past, and though it is true that he can never entirely abstract himself from his own age, it is none the less certain that his conscious purpose is a very different one from that of the whig historian … Real historical understanding is not achieved by the subordination of the past to the present rather by making the past our present and attempting to see life with the eyes of another century than our own. (p. 16)

Some, such as Russell (1984) and Henry (1997), have supported an approach similar to Butterfield’s. Bensaude-Vincent (1996) also considered the approach as a given, while recognising the value of comparisons between present and past for analytical purposes:

Though abstention from whiggism is the prime commandment of the historian of science, taking a retrospective view of a period is sometimes convenient to emphasise contrasts in scientific styles. (p. 64)

Others, such as Hull (1979), Hall (1983) and Harrison (1987), have tempered Butterfield’s line, suggesting that it may be too extreme if taken on its own and too literally. Hull concluded that

Knowledge of the present is absolutely crucial for the historian, both in reconstructing the past and in explaining it to his readers. … Warnings about “presentism” are designed to prevent our knowledge of the present from distorting our knowledge of the past. (p. 14-15)

Even taking these precautions into account, a non-Whiggish approach to the study of the history of science means that it is important to ‘set the scene’ by establishing an understanding of the reference points which determined the way people thought and acted in the era in question. This understanding requires that the
students of that history imagine themselves as being in that era as far as that is possible, and subject to the wide-ranging influences on thought which existed within the society at that time. It is only by appreciating these influences and constraints within which a scientist worked that it is possible to realise the significance of the scientist’s contribution, even if that contribution does not seem to have any direct relevance to today’s scientific understanding.

An example of this backward-looking analysis, in relation to the seventeenth century and the developments in understanding of optical phenomena, is the importance, at that time, of the notion of the ether. If viewed from today’s perspective, Descartes’ discussions of the propagation of light may be regarded as ‘wrong’ given the centrality which he accords to the motion of ether particles in explaining how light is transmitted (see Chapter 2 of Sabra, 1981). Since the classic experiments of Michelson and Morley, and Einstein’s later interpretation of them, there has been no requirement for an ‘ether’ to form part of the basis of a theory of light because their investigations could find no evidence of any effects of such a ‘substance’. This is despite their earnest attempts to confirm the existence of the ether (Shankland, 1977). The ether, which was a central component of cosmology for so many centuries, is not thought of in the same way in the latter years of the twentieth century as it was in Descartes’ time, but to impose a twentieth century understanding of the ether on an examination of seventeenth century optical thinking would not provide a real appreciation of the significance of Descartes’ contribution to optics (further discussion of the role of the ether can be found later in this chapter, section 7.3.2). The extant paradigm on which scientific theories had to be based at that time necessitated the inclusion of the ether. The ether was part of the ‘given’ (part of Kuhn’s “paradigm” or Lakatos’ “hard core” as described in Chapter 4 section 4.5.3) the existence of which was not only unquestioned but was automatically a central part of explanations of natural phenomena. The point here, then, is that it is essential to appreciate the scientific and social climate of the time if there is to be any real understanding of how scientific ideas were developed in that particular era. Continuing that analytical approach up to the present will give an understanding of the current thinking and of how earlier theories developed, without the study being a comparison between now and then.
On the basis of this approach, the current chapter examines various aspects of the historical developments in the understanding of optics by western society from the early seventeenth century until the early twentieth century. This temporal and geographic limitation is not done on account of any implied superiority of that time and place over any other, but rather as an example of how the science within a culture and the culture of science can be examined. It is not intended that what follows should be a complete socio-historical examination of developments in optical theory over three centuries, covering every important development sequentially within that period. These can be found in many different places, occasionally all within the one source (for example, Park, 1997), or often in a combination of works - for example, Lindberg (1976) covered the era from Al-Kindi to Kepler, then Sabra (1981) for the time from Descartes to Newton, and then Cantor (1983) whose discussion ranged from Newton until after Fresnel. Others have provided similar analyses during the nineteenth century and beyond. There are also numerous research articles in a range of academic journals devoted to the history of science, such as Isis, Studies in the History and Philosophy of Science, History of Science, and The British Journal of the History of Science. Rather than providing a further detailed study of history here, the intention is to highlight some aspects of that history, particularly those which illustrate one or other of the characteristics of science as described in Chapter 4, and which might be reasonably understood by senior secondary school students.

6.3 General Themes

6.3.1 Paradigms

To appreciate the way in which our understanding of natural phenomena has developed and changed during any era, an awareness of the prevailing influences and philosophies of the era is essential. These factors provide both an understanding of why scientists proceeded in a certain way and an appreciation of the significance of the work of scientists who proposed ideas which challenged those influences and underlying assumptions. This study concerning the developments in optics covers the time roughly from 1600 to 1930, and there are many periods during that era when these factors can be examined. The so-called Scientific Revolution of the seventeenth century illustrated one such period. As discussed in Chapter 4 (section 4.5.3), Kuhn (1970) referred to “paradigm shifts” as markers of scientific revolutions. When a paradigm shift occurred, it was necessarily followed by a flurry of research activity.
whereby previously explained phenomena are re-explained within the new paradigm. Additionally, the paradigm shift also prompts a new way of viewing the phenomena related to that paradigm so new insights arise, beyond the re-explanations of previously explained behaviour. This being the case, the re-orientation which occurred during the early seventeenth century was a paradigm shift par excellence as it did not just apply to a branch of science, but to science itself.

Lakatos (1970) used the notion of “research programmes” (see further discussion in section 4.5.3) which are “characterised by their ‘hard core’ … (and the) ‘protective belt’ around this core” (p. 133). He viewed this protective belt as the normal focus of investigation and testing. However, during the seventeenth century, the hard core represented by Aristotelian science was under question and eventually replaced. The essential features of the overturn of one hard core for another is described in many places, for example Westfall (1977) and Grant (1996), and, in passing, by Lakatos (1970) himself.

As in every era, there were a number of broad societal and personal influences in the early seventeenth century which had some bearing on the way in which scientific thinking developed during that time. In other words, there were factors within the field of scientific study which controlled the way a scientist carried out his or her work, and there were also external influences from the society and wider culture which impinged on the way a scientist thought. Collectively, these could be considered part of the ‘dominant paradigm’ which Kuhn referred to in describing the realm within which scientists work during any non-revolutionary period (see further discussion of Kuhn’s ideas in section 4.5.3).

Henry (1997) alluded to this range of influences and described them in some detail. Their importance, as seen by Henry, is clear in a chapter he wrote entitled “Science and the Wider Culture”:

We have noted the cultural and social context which is so often necessary to our understanding of developments in science. From wider cultural influences such as religion, and the magical world-view, to more specific aspects official organisation, such as those which form the background to developments in the status of mathematical or medical practitioners, from the links between God’s relationship with the world, correct forms of kingship and legitimate forms of scientific method, to the newly perceived need for the pragmatic innovations of elite craftsmen as a
background to experimentalism, we have seen how developments in early modern science are aspects of changes in the wider culture. (p. 86)

He continued to describe yet other topics which served as background to the Scientific Revolution. These included the link between Puritanism and Science (referred to in Chapter 4 (section 4.9) as the “Merton thesis”), the influence of the economic and political workings of the English system, the political symbolism in the hierarchy assigned to various heavenly bodies, and the mechanical symbolism of the clock in relation to cosmology.

6.3.2 The Ether

Reference was made earlier in the chapter to the ‘ether’ (section 7.2). In the seventeenth century, it was part of the central core of beliefs both in the scientific realm and in the wider European culture. The ether had particular relevance for developing an understanding of optics, but was part of the broader philosophy of Aristotle (fl. 350BC) which provided the commonly accepted framework across Europe in people’s understanding of the natural world for almost two thousand years.

In the sixth century B.C. the Greek view of the structure of the cosmos included the notion that above the earth was “aer” and beyond that was a “higher air, the aither” (Cantor and Hodge, 1981, p.3). Aristotle added an “aither” (the spelling being based on the Greek word - \( \alpha\theta\eta\rho \)) as an additional element to the four (air, earth, fire and water) which were commonly regarded at the time, since Plato, as being the components of all matter. The aither filled the space not taken up by the other four in the regions near the earth. In addition, it was the element which permeated the heavens beyond the sphere which contained the moon. It was only capable of motion, and did not combine with the other elements to produce material substances. Cantor and Hodge (1981) suggested that Aristotle saw the aither as the essential requirement for an adequate explanation of the motion of the celestial sphere:

\[
\text{for Aristotle, the circular motion so distinctive of the heavens is above all what calls for the addition of aither as an element beyond the traditional four. (p. 5)}
\]

Not only did it have a mechanical connotation for Aristotle but it also was the celestial equivalent of the earthly pneuma which was the source of the life in animate matter (animals and plants).
The widespread acceptance of an Aristotelian philosophy through to the Middle Ages ensured the similar ubiquitous presence of an aither in some form or other when describing the physical and spiritual world.

Descartes’ philosophy depended centrally on the presence of an ether (in this case the spelling was based on the Latin word – aether). For him, there could not be a vacuum, that is, a region of space in which there is nothing – he could not accept the notion of the existence of ‘nothing’. The ether filled that part of space where there was nothing else. But he did not see it as having a purely passive role. Motion, for example, occurred by means of pressure waves being transmitted through the ether from one object to another. And, important to this thesis, he developed a detailed description of how the ether transmitted light, based on the rotation of circular particles of the ether and on the pressure of ether particles one on the next from the source of light to the objects it illuminated.

Newton also relied on the ether for, amongst other things, his description of optical phenomena such as refraction. For example, Cantor and Hodge (1981) referred to Newton’s view of “light passing, say, from air into glass and so from a region of denser to one of rarer ether” (p. 21). Hakfoort (1988) also discussed “Newton’s use of the general ether hypothesis in combination with the emission hypothesis of light (in) his explanation of refraction” (p. 91).

6.3.3 Science & Religion

Another all-pervading influence on the way people thought and hence on the way scientists examined nature, came from the religious sphere. This arose in at least two contexts - in a personal, spiritual, mystical sense and in a societal, political, structural sense. At the personal level, a widespread belief in the Christian God had a profound effect on the way people thought and acted in their daily lives. Henry (1997) referred to the “individual theological views” (p.74) of people such as Descartes, Boyle and Newton, and of their attempts to maintain consistency between those views and their scientific philosophies. Henry concluded that

There can be little doubt of the importance of religious devotion in motivating and shaping early modern science. (p. 74)

Scientists in the seventeenth century weren’t removed from the influences of religion, although their effect was not necessarily obvious. Silver (1998) was of the opinion that, compared to the relationship between science and philosophy,
(t)he influences of man’s beliefs on his scientific activities has been less direct. The religious beliefs of Newton and Boyle strongly influenced the way they thought of man and the universe, but as far as their science was concerned, philosophy and mysticism were confined to their alchemical pursuits. (p. 103).

Cohen and Westfall (1995) attributed a more direct connection between religion and science:

Robert Boyle, … John Ray, … and others too numerous to mention have called on the latest discoveries in science to demonstrate the existence of God. Newton did the same. (p. 327)

And Bernal (1954), in reference to Roger Bacon in the Middle Ages, recognised the relationship which the latter had between science and religion:

For him scientific knowledge is only part, with revelation, of an integral wisdom to be contemplated, experienced, and used in the service of God. The overriding need was to justify the truths of Christianity… . (p. 226)

Bernal also observed the significance which Grosseteste, Bacon’s mentor, placed on his optical studies:

His study of light and his verification by actual experience of the refraction of lenses were undertaken because he conceived of light as analogous to the divine illumination (op. cit., p. 216)

And a final example of the connection between science and religion at a personal level is provided by Henry (1997), who described the interdependence of science and religion during the sixteenth century:

There can be no doubt that his religion was a major stimulus to Descartes’ philosophising … .The same could be said of virtually every other leading thinker in the Scientific Revolution. (p. 80)

This science-religion connection at the personal level is less widely discussed than the socio-political role which religion played within science at the organisational level. The Catholic Church, particularly in Europe, was a dominating influence on the direction of scientific development, partly in a pro-active sense, being the source of scientific thinking, and partly in a legalistic sense, deciding what could and could not be said by natural philosophers and others. The former aspect arose because many of the leading thinkers at the time were members of religious orders. The monasteries and universities run by these religious orders were the principal seats of learning. Newton himself was almost ordained a priest as an automatic requirement of his
position as Lucasian Professor of Mathematics. It was only through the intercession of his predecessor, Isaac Barrow, that this requirement lapsed as Barrow foresew potential conflict between Newton’s personal theological stance and that of the Church (Cohen and Westfall, 1995). In regard to the latter sense of the Church’s influence, Galileo’s acquiescence to Church rulings, Descartes’ subsequent tempering of his views (at least those which he published), and the execution of Giordano Bruno are some of the many examples of the restrictions which the Church imposed on scientists and philosophers, and the consequences for those who did not heed its power.

6.3.4 Lifestyle & Working Conditions of a Scientist

Information relating to the social setting within which a scientist worked is central to an understanding of the science produced (McComas, Almazroa and Clough (1998)). This linking of societal issues and science has been regarded as significant only in recent decades. This concept of a Sociology of Science has gained acceptance as a result of the work of people such as Bernal and Merton in the 1930s and 1940s, Kuhn in the 1960s, and Bloor, Barnes, Edge, Mulkay, Latour, Woolgar and many others in the 1970s and 1980s. This relatively recent interest in the working conditions and general lifestyle of scientists has meant that detailed information about the broader influences on a scientist have not been well documented.

Nevertheless, some idea of the milieu within which a scientist worked is often available from individual biographies. During the seventeenth century for instance, there have been many books written about Newton (such as Fauvel, Flood, Shortland and Wilson (1988), White (1997), Cohen and Westfall (1995)) and they have provided some insight into the personal aspects of that scientist’s life. Newton was somewhat of an exception among the natural philosophers of the time, being almost single-mindedly focussed on understanding nature to the point that he did nothing else during 1665 when Universities closed due to the bubonic plague, and he later was reluctant to become too involved in public discussion and debate of his views and theories.

For that particular era, The Diary of Samuel Pepys (Latham and Matthews (1983)) provided a unique view of the day-to-day social life of people who lived in London during the 1660s. Pepys himself was an early member (and later, President) of the Royal Society. His regular companions included Lord Brouncker, an early
President of the Society, and he was also socially acquainted with Hooke and many others. His *Diary* recorded the wide range of acquaintances which Society members had and the varied activities in which they were involved. Natural philosophers of the time, and those interested in natural phenomena, were not often solely engaged in scientific matters, but were important figures in a range of government, legal and economic circles. Hunter (1982) also provided details of the early days of the Royal Society with significant emphasis on the individual members. From a different perspective, Daumas (1972) provided some enlightenment on the work of scientific instrument makers, the type of instruments they made and for whom they made them, and an examination of factors, such as the social and economic, which contributed to the development of the instrument-making industry. Daumas’ work therefore also provided some insight into the characteristics of British society of the seventeenth and eighteenth centuries.

In relation to that period of time, developments in telescope manufacture provide some specific focus in understanding how scientists obtained their employment and what their general status in life was. Daumas (1972) and Wolf (1962) examined developments in this early optical industry. Hooke, Newton and Huygens among many others were interested in telescope manufacture and design. The common link connecting them was the Royal Society. Hooke was widely known as an excellent experimenter, in terms of design and execution, and as an expert technician with respect to his skills in manufacture of apparatus. It was this reputation which resulted in him gaining employment during the mid 1650s under Robert Boyle. The latter was a member of the aristocracy and was consequently rich enough to be able to employ his own scientist to work in collaboration with him. When the Royal Society formed during the early 1660s, Hooke was very soon appointed and employed as chief experimenter for that organisation. The connection with optics, and the telescope in particular, arose when Newton became involved with the society. At that time, while still very young, he held the chair of mathematics at Oxford University. His investigations into optics, particularly colour, were an encouragement for him to communicate his ideas to the society although he was relatively unknown to its members at the time. The method he used to acquaint himself with that group was initially by submitting a new telescope design to overcome the chromatic aberration problem which had previously existed. This approach, he hoped, would give him sufficient recognition to enable him to then elaborate on his theory of light
and colours. Further details of these developments are more appropriately discussed later (section 7.3.6).

Hooke was employed by the Royal Society, Newton was financed by Trinity College at Cambridge University, initially as a tutor, and later as a professor. His employment conditions required him to eventually become a religious minister, but his outstanding knowledge enabled him to circumvent such requirements through the intervention of some close friends. Huygens, working on optics in France had a different financial status to the others. He was initially employed as a personal scientist to Louis XIV and later was employed as a scientist for the Acadamie des Sciences.

It is opportune then to discuss modes of employment and larger funding processes to illustrate that science is not unlike other institutions within a society, all of which need a financial system if they are to operate coherently at any level above that of an individual hobby or small interest group.

The broad descriptive images which can be gleaned from such sources help to create the background tapestry to the scientific developments which helps to illustrate and emphasise the idea that science is, in the end, a product of people working at a particular time and not just a textbook of dogma.

6.3.5 Societal Influences During the Early 1600s

Until at least the 1640s, when the so-called Invisible College in Oxford began to meet, the environment in which science took place was largely a personal one because there were no established scientific societies nor was there any broadly based funding of scientific investigations (Ziman, 1976). Although there were universities in many cities at and before that time, they did not have a tradition of any form of scientific research. As Westfall (1977) pointed out, such institutions were the principal centres for opposition to the new conception of nature which modern science constructed. (p.105)

It was only the sufficiently rich who could afford to be involved in any of the detailed experimental and observational science initially advocated by Grosseteste and Roger Bacon in the thirteenth century and formulated into a new philosophy by Francis Bacon and Descartes (see later section 7.3.7), separately, in the seventeenth century. Alternatively, some science could be undertaken by those fortunate enough
to have a position in the royal court of a country’s monarch. By the 1660s, the Royal Society of London and the *Academie des Sciences* in Paris were formed and gave scientists the opportunity to meet regularly and to exchange information and ideas formally and publicly.

During the late 1500s and early 1600s the spread of scientific knowledge took place among the educated upper-class members of society - those who could afford to devote much of their time to comparatively leisurely pursuits - Henry (1997) referred to the “gentlemanly circles which produced the new science” (p.92), and Wolf (1962) wrote of “the class of rich scientific amateurs” (p.273). To an extent, science in those times could be seen as an activity undertaken by certain members of society as an intellectual pastime as much as it could be considered a formal institution within society. Ziman (1976) described the situation of many scientists in 1670 in the following manner:

Natural philosophy was essentially an obsessive hobby, in which a physician, a professor, a priest, a monk, an aristocrat or even a shopkeeper could indulge himself, just as nowadays he might take to rock-climbing or chess. In an age when there was genuine leisure for many members of the upper or middle classes, research was almost entirely an amateur activity for a few well-educated or intellectually curious enthusiasts. (p. 46)

The vast majority of the population was unaware of any scientific activity and certainly saw little evidence of it in their lives. Workers in a few of the crafts were the only ones who had links with both groups; although themselves members of the general public, they were nevertheless in contact with the community of scientists due to their instrument-making skills. This contact would not have been sufficient for the craftsmen to have any understanding of what was being done, if for no other reason than the product of scientific undertakings had no direct relevance to them; there was little in the way of immediate technological applications emanating from scientific endeavours at that time. The scientists themselves were also members of the ‘general public’ but their discussions of ‘natural philosophy’ were reserved for times when they were with other natural philosophers and those interested in such pursuits. Certainly, Pepys’ *Diary* does not give any indication that there was significant dialogue about scientific matters in general discussions or conversations reported in his record of day-to-day life. The general public of the seventeenth century were much less aware of natural philosophy than today’s public is of science.
The personal motivation for undertaking and sustaining scientific activity in those times differed from later eras due to the personal nature of scientific pursuits. External rewards and recognition have certainly increased over more recent times, probably beginning with the formation of scientific societies in the later 1600s. These provided a forum for discussion, debate and constructive criticism, as well as ideas for new directions of investigation. Soon after their formation, such societies began to produce journals. The combination of these two outlets not only provided great impetus to the growth of scientific knowledge, but also gave scientists a basis for public recognition. This greater profile and associated public recognition eventually lead to science being a realistic career path.

By the eighteenth century, the connections between science and industry and engineering became more numerous and significant, providing further opportunities and forums for reward and recognition. This would have been a significant motivating force and reward for scientists, one which had not been present in pre-scientific days. Even within the more ‘academic’ scientific sphere over the last few centuries there has been a wide and complex network of people, scientific societies and publication media all of which gave rise to many possibilities for differing motivations than those which existed in the early years of the scientific revolution. Financial gain, widespread acclaim, and even the more pragmatic “science as a means to earn a living” were not significant among the rewards sought by those who developed scientific interests in the years surrounding the scientific revolution.

6.3.6 The Interdependence of Science & Technology Progress

The scientific revolution of the seventeenth century saw a rapid increase in the type and number of instruments being made as described, for example, by Daumas (1972). Instruments lead to scientific discoveries (for instance, the telescope provided crucial evidence in support of the heliocentric solar system), and scientific discoveries led to new or vastly improved instruments (for example, the discovery of the cause of spherical aberration demanded that parabolic lenses be made). In addition to the improvements in engineering design and the craftsman’s technique in producing better instruments, there also were developments in production technology which resulted in higher quality of manufactured materials - glass, for instance, underwent a significant improvement in uniformity of composition which enabled greater
precision and magnification in various optical devices (see, for example, Derry & Williams (1960)).

Quality of optical glass was also a central issue in the 1830s debates involving Brewster, Powell, Fraunhofer, and others regarding fine measurements of the lines in dispersion spectra. Greater and more easily replicable detail was possible with dispersion of either monochromatic or white light passing through a gas contained by a hollow prism rather than with prismatic dispersion in solid glass, because of the difficulty of obtaining “sufficiently pure glass” (Chen, 1998, p. 410). Chen also commented on the difficulty which the same workers had in obtaining similar measurements for diffraction of light from a grating:

The key obstacle was the extremely complicated technique of making gratings. (p. 414)

Their efforts at the time centred around a debate about whether a wave theory could be successfully employed to explain light dispersion. Difficulties existed not only because of lack of sufficient technological success in producing glass of uniform quality but also because of other differences related to the technology they employed. For example, the actual pieces of equipment used in those investigations were not identical for each scientist, each having their own idea of how best to produce a full set of dispersion lines. Powell used a theodolite to measure angles of refraction whereas Brewster’s main item of equipment was a small but powerful telescope which enabled him to see many dispersion lines but he was not able to measure them accurately. He did not see that as important because his observations lead him to decide that the many lines were chemical in origin, based on the material between the light source and the observation equipment. Brewster also saw experimental investigation primarily as a means to educate the public rather than to obtain optimum precision in measurement. Consequently, the explanations and results they produced were, according to Chen (1998), ultimately based on different experimental paradigms which were “shaping scientists’ opinions” (p. 401). As a general observation, Chen asserted that

It is crucial to adopt a historiographical perspective that fully appreciates the role of instrumentation. (p. 403)

The serendipitous ‘discovery’ of the telescope was itself a product of technology, as it is usually presumed, for example by Bernal (1954), to have arisen
“as a by-product of the manufacture of spectacles” (p. 292) when someone inadvertently viewed a distant scene through two pairs of spectacles, one being some distance away from the wearer. This led to the production of what Zajonc (1993) understood to be called “perspective glasses” (p. 74) which Galileo thought to use to more closely inspect heavenly bodies. Imperfections were seen on the surface of earth’s moon, moons were seen to be orbiting other planets and phases were observed for Venus. The development of new optical instruments was prompted through technological inventions and the result was no less than a different view of the universe, although this did not occur in as straightforward a way as might be thought if considered from the perspective of the present, as is so often the case in rational reconstructions of events at the time. Poole (1990) indicated that there were those who attributed the unexpected observations to imperfections in the lenses, a well-known problem at the time due to the difficulties associated with grinding accurately-formed lens shapes. Others simply refused to look through Galileo’s telescope, usually offering the lens imperfections as their reason, but more likely being unwilling to have to admit to the existence of something which would seriously question lifelong beliefs, reputations and Church teachings. There was even a reluctance among those who did deign to look through the telescope to accept the presence of planetary moons and other observations which Galileo claimed visible. In those times the then new device, the telescope, was not even accepted as an instrument of science in the same way as it is now; in addition, the use of such an instrument required some specialist skills to correctly interpret what was seen. Shapin (1996) summarised the situation as follows:

It is right to say that instrumentally mediated experience of the heavens figured importantly in the evaluation of astronomical theories, it is vital to understand how precarious such experience might be and how much work was required to constitute it as reliable. (p. 73-74)

Not only did technology influence science but the reverse could also be seen, again, telescopes provide an illustration. Newton’s understanding of the nature of white light suggested to him that chromatic problems with refracting telescopes were inherent in the nature of the instrument and this prompted him to work on reflection as a basis for design. As occurs so often in history, however, the discovery and development of the reflecting telescope was not as simple nor as linear as might be implied by the previous statement. While Newton certainly was an early worker on
reflector design he was by no means the only one nor necessarily the first. In describing early investigations into reflecting telescopes by Mersenne, Cavalieri, Zucchi and many others, Ariotti (1975) observed that

there was considerable interest in and experimentation with reflecting mirrors and telescopes … before Newton’s discovery of the nature of white light and chromatic aberration. (p. 319)

The same researcher nevertheless recognised Newton’s position historically by granting that “the realization of the reflecting telescope had to wait for Newton and 1668” (p. 319). The term ‘realization’ does not carry quite the same connotation as ‘discovery’. The former term implies a culmination of efforts over a period of time, whereas the latter suggests more of a single-handed contribution occurring in a short space of time. It was therefore not the case that reflecting telescopes arose as solely a result of Newton’s understanding of the nature of light behaviour, although it was certainly a contributing factor, for Newton at least. Ariotti indicated the mutual development of science and technology in the affair when he reported that the same “experimentation with reflecting mirrors and telescopes”

led to considerable theoretical groundwork: not only were all the essentials of reflecting telescope understood and demonstrated, but also the very concepts of the four main type of reflecting telescopes were grasped before the impact of those men after whom the telescopes were later named – Gregory, Newton, Cassegrain and Herschel. (p. 319)

This emphasised the importance of technology, not only as a separate discipline used on occasion by science where necessary, but also as an activity interwoven with science in the development of scientific theory.

6.3.7 Descartes, Bacon and Galileo

In the early decades of the seventeenth century a mechanistic view of the world was developed systematically by René Descartes. His work was one of the principal influences in setting in train the eventual revolution in science which was to occur (Ribe, 1997). The method of analysis of natural phenomena which he advocated arose from a wider and more fundamental position he developed in relation to a universal philosophy based on logic and reasoning. At the time, Aristotle’s natural philosophy was still widely held (although there were the beginnings of some scepticism towards it being shown by 1600) and was based on there being a fundamental difference in understanding the way in which the driving forces for
celestial and earth-bound phenomena operated. Descartes proposed a more universal view, having just one framework of understanding. Descartes’ mechanical philosophy had become the dominant one by the time of Galileo’s death in 1642. He used the structure of the eye and an analysis of vision to illustrate his philosophical approach. Subsequently, he became involved in a discussion of optics, although this work also arose through his general interest in the nature of the world. Explanations of phenomena had to be in terms of interactions between physical objects rather in relation to the influence of humours, spirits, virtues or the soul, as had been the case previously. Nevertheless he was guarded in expressing his opinions during the 1630s, being mindful of the Church’s actions towards Galileo and others who proposed any beliefs about the way the universe was constructed if those ideas were contrary to Church teaching. In Bair’s (1961) translation of Descartes’ *Discourse on Method*, the latter explained that “certain considerations” (p. 25) prevented him from publishing an earlier treatise (The World) in which he would have described “everything I thought I learned ... about the nature of material things” (p. 25). The *Discourse* contained Descartes’ view of the fundamental features of existence and his elaboration of a method of gaining new knowledge.

Bacon was also advocating a logical approach to investigations of nature, although his idea was to base theory on an analysis of the characteristics of a particular natural phenomenon and on the results of carefully constructed and controlled experimentation. From these results, theory could be constructed inductively and further modified by a process of falsification. While Descartes was in agreement with the essentials of Bacon’s approach, the former relied more on deductive logical thought processes for theory construction, while the latter began with the experiments and observations themselves and arrived at a theory inductively. Sabra (1981) explained that Descartes formulated a priori principles which were “developed not only independently of experiment but, sometimes, against the verdict of experiment” (p. 26). And further he noted that

While Descartes recommended Bacon’s view regarding the making of experiments, and even followed his example in the collection of natural histories, he completely ignored induction as a method of deriving general propositions from experiential data; moreover, his view of the role of experiment and observation was diametrically opposed to that of Bacon. (p. 35, Sabra’s emphasis)
Prior to the time of Descartes and Bacon, others had begun to apply the approach which those two advocated, but without consciously doing so under the banner of a new philosophy. Most notable in this regard was Copernicus who developed a theory based on observation in a style of which Bacon would have approved. But the ‘formal’ introduction of a new philosophy came as a result of the work of Bacon and Descartes.

Having developed a different way to view, analyse and explain the natural and physical world, Descartes applied his thinking to the field of optics to illustrate his method of reasoning. Bacon specifically advocated a rigorous experimental approach based on careful design and observation. Although these ideas helped set the course of the Scientific Revolution, their implementation by other natural philosophers at the time was not widely adopted. The notion that events have physical cause was another characteristic of the new philosophy and it was incorporated into the development of new understandings of natural phenomena before careful experimentation was widespread in the development and testing of new or tentative theories. As Westfall (1993a) noted, at this time “experimentation … was still a novel procedure” (p.42). Westfall also noted, however, that experimentation did exist prior to that time, but, during the 1600s,

> [it] became, in a way that it had never been before, the distinctive method by which science pursues the knowledge that it seeks. (p. 41)

On the European continent, a logico-mathematical approach had developed, partly under the influence of Descartes. This contrasted with the more hands-on practical tradition which was stronger in Britain, undoubtedly through the ideas of Bacon. A notable example of the latter could be seen in the approach taken by Newton in his study of optics, and particularly in his self-titled experimentum crucis (described in many places, for example Fauvel, Flood, Shortland, and Wilson, 1988) in his attempts to come to an understanding of the nature of colour. In the introduction to his book, Opticks, he stated that he intended to explain the properties of light “by Reason and Experiments”. On the continent experimentation was not absent either. For example it was Grimaldi in Italy whose experimental work (according to Park (1997), his “passion was experiment, very refined and exact”, p. 189) led him to observe a fine set of lines along the edge of a shadow (diffraction).
During the same era as Bacon and Descartes, Galileo left his own mark in terms of his approach towards practical investigation and also regarding the connection between the explanations of science and the real world itself. His investigations into motion laid the foundation for the work of Newton in the *Principia* later in the seventeenth century. Unlike those before him, Galileo no longer regarded motion as an innate property of an object as Aristotle had. His explanations were based primarily on idealisations and he was unmoved by any difference between the ideal and the real. As Westfall (1977) explained it,

> To Galileo, the real world was the ideal world of mathematical relations. The material world was an imperfect realization of the ideal world on which it was patterned. To understand the material world adequately, we must view it in imagination from the vantage point of the ideal. Only in the ideal world do perfectly round balls roll forever on perfectly smooth planes. (p. 22)

Henry (1997) similarly recognised the new directions set by Galileo when he suggested that,

> Perhaps his greatest contribution to the development of science was … his exemplification of the usefulness and success of the mathematical approach to nature. … mathematical practice can help us to understand the nature of the world; even in those cases where the fit between mathematical analysis and physical reality is only approximate, the mathematics being based on idealized, and unrealizable, circumstance. (p. 18)

### 6.4 Newton

There is much that can be learned about the characteristics of science and the nature of scientists from a study which centres around the life, times, work, character and personality of a particular scientist rather than focussing on conceptual developments. This is especially so in the case of Newton about whom so much has been written which is readily accessible to teachers and students in secondary education. His contribution to optics can be suitably used as a reference point for such a study. There are numerous scholarly works which have been written about Newton and it is not the function of this research to reproduce or redefine the significance of the person or his era. However it is appropriate to provide some illustrations in relation to Newton to indicate what can be relevant to the development of a curriculum program based on the design framework of Chapter 6.
Like scientists anywhere, Newton had a range of interests and this is often overlooked in traditional discussions of him in school textbooks. Mathematics, optics, astronomy and mechanics normally define the boundaries of discussions about him, even though he was interested in other areas of what might be considered as science. These include alchemy which was a very different pursuit to the chemistry which followed it in later years. Elements of the mystical, spiritual and secret were fundamental to the practice of alchemy and Newton’s work in this area contrasts with much of his more well known contributions. Fauvel, Flood, Shortland and Wilson (1988) provide a valuable starting point to a more detailed understanding of this aspect of Newton’s life. White (1997) has described this facet of Newton’s life in much detail, suggesting that “(h)is alchemical work and his science were inextricably linked” (p. 5) and argued that the former had significant influence on the latter. The religious dimension in Newton’s life has been referred to by Dobbs and Jacob (1998) and others, and again there is clear indication of the interweaving of Newton’s religion with his attempts to explain the natural world.

Newton’s communications with others help to paint a picture of his personal qualities as well as demonstrating the various ways in which scientists interacted with each other in their endeavours to understand natural phenomena. On various occasions, Newton can be seen to be polite and reserved (for instance in his initial correspondence to the secretary of the Royal Society regarding his optical discoveries), very annoyed (in another letter to the secretary when Pardies wrote to the Society from France casting doubts on Newton’s key optical experiments), openly argumentative (in his communications directly with Hooke or via the Society regarding accrediting Hooke with any influence, no matter how small, on his ideas about colours and other phenomena), proud of his personal achievements which he considered as being completely his own (illustrated in the same series of altercations with Hooke), and many other characteristics besides. These and many other aspects of his personality have been illustrated in the contributions of Christianson (1996), Sabra (1981), Weinstock (1992) and Westfall (1993a and 1993b).

Newton’s annoyance at criticism from others and his fundamental approach to understanding the universe are both illustrated in the way he responded to accusations that his corpuscular view of light and colours was merely conjecture or ‘hypothesis’. The suggestion was that he had arrived at a description of light without having the
firm observational and experimental basis which the philosophies of Bacon and Descartes would have demanded. His assertive response to such allegations was the oft quoted ‘hypotheses non fingo’ – I don’t invent hypotheses - indicating that he was describing actual properties of light rather than making an unsubstantiated proposal of what light might be. Sepper (1994) described the hypothetical method of some of Newton’s contemporaries as “proposing and unverified and perhaps unverifiable mechanism underlying appearances” (p. 37), whereas Newton “believed that it was possible for natural philosophy to provide greater certainty than hypotheses” (p. 37). Crombie (1957) explained that

(Newton’s) often misinterpreted dictum … did not mean that he never made hypotheses, for he made many; he drew a distinction between generalisations of experimental data, as expressed in a mathematical formula, and physical hypotheses advanced to explain the cause of the observed phenomena. (p. 397)

Newton was not only concerned with painting nature with the broad brush. He also involved himself with the day-to-day detail of producing his own materials which he required to enable him to conduct his investigations. Sepper (1994) referred to Newton’s efforts to grind his own lenses, including those which were non-spherical in shape. Daumas (1972) was another who highlighted Newton’s work in relation to the technology of lens-making and his revolutionary telescope design based on his theoretical understanding of the problems inherent with lenses. The same author also described the work of Newton’s contemporaries in the field of optical technology, but these were largely craftsmen such as Borel who advertised their skills to the Royal Society and elsewhere, but who did not perform their work with the same theoretical understanding which Newton had.

6.5 Developments in Optics - Concepts and Interpretations

6.5.1 The State of Optics in 1600

Optics did not begin as an area of study in the seventeenth century – there were many who studied sight and light throughout the centuries and in many civilizations. Nor was optics the single discipline that it is today. Lindberg (1976) referred to a “philosophy of light” (p. 95) which included, among other things, links to God as the ultimate source of light, even in a literal sense for Augustine, for example. Light was also involved in concepts as disparate as the creation of the world and the source of truth.
Some of the most significant contributions to the physics dimension of light were made by initially by Aristotle, Euclid and Ptolemy, the latter, for example, undertaking sufficiently detailed measurements of refraction angles to attempt a mathematical treatment for a law of refraction, as described in Park (1997). Their work became the basis for later studies in optics throughout the Islam world. As Lindberg (1976) pointed out

if we wish to understand medieval and Renaissance theories of vision, we must begin by glancing at the Greek background. (p. 1)

Aristotle was concerned with the physical nature of light and vision whereas Euclid described light’s properties mathematically and geometrically. Later, in the eleventh century in the Middle East, Alhazen combined elements of both approaches to develop his theory of vision which included physical, physiological and mathematical components. It was from Alhazen’s work, according to Lindberg, that the Western optics grew. This occurred through contributions and interpretations by Grosseteste and then Roger Bacon in the thirteenth century. Lindberg’s (1992) summary of the situation was that

when Johannes Kepler began to think about visual theory in the year 1600 … he took up the problem where Bacon (and Pecham and Witelo left it. (p. 315)

Although there had been some who applied mathematics to optical properties as indicated above, the use of mathematics in science was not the fundamental part of science that it is today, nor had the mathematical concepts been developed which are now used today. Henry (1997) highlighted some of the changes which occurred around the time of the Renaissance. Symbolic algebra was adopted as means of representing unknown quantities in arithmetic and trigonometry in the late 1500s by Vieta. Decimals were introduced around the same time and logarithms some thirty years later. The applications of such techniques and concepts in optics naturally could not have occurred prior to that time.

6.5.2 An Analysis of the Seventeenth Century Theories

The interest in light in the early years of the scientific revolution focussed on an “analogical understanding of light” (Zajonc (1993) p.111); light was “viewed as like something else”. In the early years of the seventeenth century, Descartes developed a physical vibratory model which involved a form of motion of the ether but he explained refraction using a tennis ball analogy.
In their attempts to explain light, natural philosophers and scientists have proposed a range of theories which have often been allocated to one of just two categories: particles (or corpuscles or projectiles) and waves (or undulations). Discussions of such views, particularly in many standard educational texts and secondary physics curricula, have implied, if not explicitly stated, that each of these two theories referred to a specific and clearly defined set of explanations (for example, Haber-Schaim, Dodge and Walter (1971)). Further, the impression has often been given that these two views were fixed in their description (the wave theory and the particle theory) and that scientists were collectively, cooperatively and simultaneously attempting to decide on the correct view (for example, Mayfield, Parham and Webber (1972)). This could be regarded as the ‘received view’ on the subject as far as secondary school physics education is concerned. Ingram, Kuhl, McCarthy, Sandercock, Smith and Waite (1971) actually separated the theories in time when they summarised

Early scientists thought that light was corpuscular while we have used a wave model for light. (p. 52)

Cantor (1983) suggested that the dichotomy could be due to our twentieth century understandings of light being imposed on optical discussions in the earlier centuries - the dichotomy “is clearly of great significance to present-day physics” (p. 11) - rather than to any historical accuracy; or perhaps it had its origins in the Newtonian dominance generally, and therefore of light theories in particular, until a successful wave-based theory was accepted.

Rather than two theories, Cantor (1983) has suggested that a four-way categorisation may be more instructive for analysis. He preferred to divide the wave theory into two separate, but not completely independent, theories, the extra one being called vibration theory. A fourth theory was the fluid theory by which light, like heat and electricity, was compared to water. Cantor’s suggestion that there were more than two theories may, however, be creating more divisions than even the natural philosophers at the time recognised, since they often referred to the one or other theory as if there were only two. Cantor does accept that the fluid theory, at least, may have been or become “peripheral” and the wave and vibration theories had much in common. This situation notwithstanding, the four-way division is still useful as a means of more carefully describing and analysing the theories. James (1984),
while still referring to the two-theory idea, at least recognised that it was “a gross over-simplification, since there were many varieties of each theory” (p. 47). What follows is an examination of the theories of light on the basis of Cantor’s four theory-types.

61.5.2.1 Projectile Theories

Newton is generally regarded as the designer of the projectile theory. While it is appropriate to refer to the Newtonian model of light, there is less accuracy associated with the notion that it was the projectile theory or that the views on light held in the eighteenth century were Newtonian.

The basis for Newton’s corpuscular theory can be related to his wider view that all of nature can be explained by forces which exist between material substances. Accordingly, light would need to be particulate if it were to be incorporated in the same set of philosophical bases for explaining the natural world. This is not to suggest that Newton consciously opted for particles, having examined what was required for philosophical consistency, but rather that, in reducing nature to interactions of forces, he would, as a matter of course, consider particles of light. Whenever a direction change occurred, a cause was required to cause it (according to Newton) and the force necessarily acted on something; light experienced direction changes (such as in reflection, refraction, dispersion and diffraction in particular) so Newton (1730/1979) argued, in *Opticks* (Book 3, Part I, Quest. 31), that a force must be exerted on the particles of light to account for these behaviours:

![Equation]

Have not the small Particles of Bodies certain Powers, Virtues, or Forces, by which they act at a distance, ... upon the Rays of Light for reflecting, refracting, and inflecting them (p. 375-376)

Sabra (1981) described how Newton, in explaining refraction for example, postulated a narrow region along the boundary between two media and the light particles within this region experienced a net attractive force towards the more dense material. If this force were constant, the light would follow a parabolic path, as do objects in a gravitational field.

Newton was able to derive an expression which was consistent with what these days is referred to as Snell’s law (the sine ratio of incident and refracted angles is constant). The complexities surrounding the eponymy are further described later in section 7.5.7. In addition, for light travelling towards a less dense material, Newton
showed that there would be an angle beyond which light would be attracted back into the more dense material and so be totally reflected. Seger (1994) described Newton’s efforts to explain the observation that light is partially reflected and partly refracted at the surface of a transparent material. Newton introduced the notion of “fits of easy transmission and reflection” (p. 140). This concept ascribed cyclical properties to light particles which resulted in them being able to either reflect from or pass through the boundary region between two media. This also involved a property which is more commonly thought of as being wave-related: the notion of a wavelength, which Newton (1730/1979), in proposition XII of Book II Part III of *Opticks*, called the ‘interval of fits’ and was the distance which a particle moved as it changed from being in a ‘fit of easy transmission’ to a ‘fit of easy reflection’ and back again. In discussing dispersion, Newton attributed different colours to different particle size. His initial explanation of the fringes seen in diffraction was that it was probably a form of refraction resulting from a decrease in the density of the aether in the region very close to the surface of the opaque object. Objects were opaque because, as recalled by Badcock (1962) they contained pores so large that light particles could “get lost and become absorbed into the body” (p. 105).

Throughout all of this - a period of time spanning some forty years from his first optical experiments in the mid 1660s to the publication of *Opticks* in 1704 – Badcock (1962) and Shapiro (1993) have suggested that Newton was not primarily concerned with deriving a theory for light, nor was he a completely committed advocate of a projectile theory. Some of his descriptions of light behaviour involved aspects of ‘wave’ properties such as the vibrations which light particles caused in the aether, and the vibrations of light itself in his explanation of the colours of thin films. Badcock wrote of Newton’s work in the Royal Society:

*(The Corpuscular Theory) was advanced in detail by Newton in papers read to the Society in 1675 and 1676, although, being much more interested in effects than in theories, he was not at all dogmatic in his views. However, he favoured the corpuscular theory because it seemed better at explaining rectilinear propagation … (p. 100).*

and, in relation to a paper published by Newton in the early 1670s, Shapiro observed that
Newton unabashedly works with an emission theory of light in which the light corpuscles excite vibrations in the aether, but he does not set out a systematic description of either the phenomena or his physical hypothesis. (p.60-61).

During the first decades of the eighteenth century, after the publication of *Opticks*, there were many in England who made determinations of the size of light particles, explained the ways in which matter could exert forces on light particles (particularly in order to explain reflection, refraction, dispersion and ‘flection’ - diffraction) and described the way in which light particles could either pass through transparent objects or be absorbed by opaque ones. Cantor (1983) described these developments and variations in the projectile theories, including the works of Cheyne, Robert Smith, ’sGravesande, Worster and others. All of this work was based on the dynamics of forces to the extent that Cantor suggested that Optics was a branch of Dynamics during the first half of the eighteenth century, and that the projectile theory had become “institutionalised” by 1740.

Later in the same century, Brougham and Herschel separately researched the phenomena of refraction and diffraction, the first two basing their explanation on forces of attraction and repulsion which light particles experienced as they passed from one medium to another or close to material objects, while the third employed only attractive forces in his explanations. Badcock (1962) noted the difference between Brougham’s and Newton’s views regarding diffraction in that Brougham “stressed that there was no need to assume any atmosphere, whether ethereal or electrical, around objects” (p. 113).

The projectile theory continued to enjoy widespread acceptance during the early part of the nineteenth century, although the wave theory gradually overcame it so that, by about 1850, there was little support remaining (see also later in this Chapter, section 7.5.8).

**61.5.2.2 Vibration Theories**

Another commonly held description of light during the seventeenth century was what Cantor classified as the ‘vibration theory’. It was based on a description of the ether in which there was some vibratory motion of the ether particles or at least a “tendency to motion”, as Descartes described it. Hooke’s view was that light was actually a “vibratory motion transmitted through the ether” while Huygens regarded it as “an ethereal pulse” (Cantor, 1983).
As Descartes was a significant figure in the shaping of views of light in the early years of the scientific revolution and his approach to scientific investigation was widely respected, it is appropriate to examine the way he applied his philosophy to a particular field of natural study.

Descartes did not intend to develop a complete theory of light as he was not primarily interested in the study of optics per se. Rather, his prime purpose was to show how his scientific method could be applied in specific situations to arrive at an increased understanding of some natural phenomenon. Nevertheless, he developed a sufficiently detailed explanation of the nature of light, based on it being an interaction between the particles of the ether as the transmitting medium, that Sabra (1981) conceded that

we may regard Descartes’ theory of light as the legitimate starting point of modern physical optics. (p.48)

The principal optical phenomena examined by Descartes were refraction (and reflection as a preliminary study of refraction) and the formation of rainbows. Both had been central to studies of optics over centuries - the former from the point of view of developing some law, or at least a detailed and accurate description of the phenomenon, and the latter because of its inherent interest to people for a range of reasons which included the spiritual as well as the scientific.

Descartes suggested that a ray of light was the line of the action along which the ‘tendency to move’ was directed within the ether. Using these rays of light he described light’s behaviour purely in terms of geometrical diagrams, although he also drew analogies between light and the motion of a tennis ball. This was not so much to suggest that light was particulate but merely to illustrate that the paths taken by light and material objects were the same. However Sabra (1981) commented that Descartes’ approach was

too geometrical to allow anything much being done to it mathematically (because)
the points on the rectilinear rays had to be made successive, not simultaneous (p. 210, footnote).

This arose because of Descartes’ belief in the instantaneous motion of light (see further discussion later in this Chapter, section 7.5.6). In explaining refraction, he attributed a variable rotational motion to the globules which, he conjectured, comprised “subtle matter”. This latter is what Descartes suggested was the “second
element” or the material of the heavens between the stars and the earth (Sabra, 1981). These globules attained their rotation as a result of the differential ‘movement’ between rays on the edge of a light beam and the adjacent globules which were not in the beam. Differential rotational speeds related to different colours.

Some thirty years after Descartes, Hooke became interested in an explanation for light for which he drew heavily on the ideas of Descartes. Despite the rule which the Royal Society held regarding the making of statements based on experiments rather than being pure conjecture, Sabra (1981) suggested that Hooke adopted Descartes’ idea that the ether was the medium which was the “vehicle of light” (p.187). This use of the ether may have had as much to do with its paradigmatic status at the time as it did to do with any conviction which Descartes conveyed. According to Ronchi (1970), Hooke held that

light was due to a motion of matter, a motion which had to consist of vibrations because had it been otherwise it would have led to the disintegration of the luminous object (p. 151).

Hooke went on to interpret Descartes’ explanation of refraction based on a ratio of sines by considering two adjacent rays of light travelling obliquely towards the surface of a refracting medium and to refer to the line joining two impulses, one on each ray, which left the luminous body simultaneously. In other words, he employed the notion of a wavefront and discussed the directions which it would take if it passed into a refracting medium through which it could pass more or less easily.

In the following century, vibration theorists included people such as LeCat (in France in the 1740s and 1750s) and Euler (in Germany during the same period). LeCat’s view of light differed from Descartes in that he, LeCat, considered light to be actual motion in the particles of the body transmitting the light and of the ether. Euler, similarly, and in mathematical detail, described the harmonic oscillatory motions of ether particles and related the frequency of vibration to the colour of the light. According to Cantor (1983), he also proposed that

bodies could interact with other vibrations in any of four ways; this classification corresponded to whether the bodies were lucid, reflecting, transparent or opaque (p. 120).

At the end of the eighteenth century, Thomas Young, trained in medicine but interested in a wide range of natural phenomena, had examined aspects of vision and
acoustics, and this led him to an interest in the ether and eventually to become, according to Cantor (1983), the vibration theory’s “most able defender” (p. 131). This may be considered somewhat surprising given the normal association of Young with the introduction of the wave theory of light. However that view is based on the idea that there were two theories of light. In that case, Young would be ranked with the wave theorists, but, in Cantor’s four different light theories, Young was included with the vibrationists. He, Cantor, quoted Young as distancing his interference work from his more general studies of light:

(The interference law) was ‘totally independent of any opinion of the nature of light, and appears to be deduced from a simple comparison of incontrovertible facts’. (p. 132, quoting from Young’s notes)

Elsewhere Cantor (1983) noted that Young “distinguished between the law of interference and the hypothesis of vibrations” (p. 140, his emphasis). Ronchi (1970) recorded what Young had written in Philosophical Transactions in 1802:

wherever two portions of light arrive at the eye by different routes, either exactly or very nearly in the same direction, the light becomes most intense when the difference of the routes is any multiple of a certain length … and this length is different for different colours (p. 237, my emphasis).

In noting the mathematical relationship between the two light paths, Young did not actually refer to ‘wavelengths’. If the nature of this ‘certain length’ was not apparent to him at that time, by 1807 he had more clearly related it to a wavelength. Nevertheless he still appeared to be tentative about the wave nature of light when, in Lectures on Natural Philosophy, Wood (1954) pointed out that he referred to the path differences which occur to produce maxima in the ‘double slit experiment’ as “one, two, three or more, of the supposed undulations” (p. 177, quoting from Young’s publication). Young’s lectures were not all that well received by his contemporaries and appeared to do little to convince them to change from the Newton-dominated projectile theory. Cantor (1983) noted the “poorly received” (p. 136) lectures given by Young at the Royal Institution contrasting with his papers delivered to the Royal Society. Park (1997) suggested that others were so uninterested or unconvinced by Young’s ideas that they did not even bother to repeat “his experiment to make sure it had been done right” (p. 251). This may also have been because of the lack of clarity which characterised much of Young’s work. As Cantor (1983) described it,
If we avoid the luxury of hindsight Young’s papers pose considerable problems of interpretation. … We do not find a coherent theory of light but instead gain glimpses of a working scientist wrestling with a number of thorny problems. His explanations varied from one paper to the next, he reformulated his principle of interference, he reverted to rough analogies when concise formulations were needed, and his discussion of important issues was sometimes obscure and always too brief. (p. 131)

Throughout all of this he assumed, as did all others before him, that the vibrations were longitudinal as distinct from transverse. This was not as a result of making a conscious decision between the two but was a natural consequence of the way in which the vibrations were described as being transmitted through the ether. It may have also been due to the frequent connections made by many between light and sound and the understanding sound transmission. Despite the reference to wave concepts here, Young was still a vibrationist.

Contrary to Newton’s view of the density of the ether, Young suggested an attraction between ether and ordinary matter so that its density was less at greater distances from matter. Cantor (1970) pointed out that this work which concentrated on the ether in relation to light was part of Young’s broader study of the ether as a basis for explanation for a range of phenomena including heat, electricity and magnetism. Much of what Young undertook in relation to the vibratory nature of light was not so much his own as it was a drawing together of the ideas of others to develop a more comprehensive explanation of a range of phenomena and to account for criticisms of the vibration theory (Cantor, 1983).

61.5.2.3 Fluid Theories

According to this view, light was a particulate substance, emitted from a source, as described by the projectile theory. Although, like all other theories, fluid theories involved some motion of or interaction with the ether, descriptive differences between fluid and other theories - especially the projectile ones, were apparent in their denial of attractive and repulsive forces between light and matter. More fundamentally, the ether was regarded as the source of many phenomena, and the significance of fluid theories was in the connections they attempted to make between a range of phenomena such as light, heat and fire which were all treated as a type of fluid. This approach was distinct from the mechanical approach of Newton or Descartes and often had more to do with cosmology. Fluid theories tended to be less...
reliant on mathematics as a means of describing light phenomena in a quantitative fashion. Their adherents were, according to Cantor (1983), an eclectic group whose members included Fellows of the Royal Society, those who worked in law, and some who were in religious communities.

These theorists were a more diverse group in personal background and in theory description than other groups. Some were clergy or influenced in some other way by religious beliefs, others, because of their academic interests, adopted a chemical philosophy after the style of Boerhaave. In the seventeenth century, his ideas were developed on the basis of a close connection between light and fire which, he conjectured, were both composed of particles. He attempted to relate his particles to Newton’s ideas, suggesting that fire, like light, also consisted of seven types. Hutchinson, who first published in the 1720s, developed a more theological view of light as a manifestation of the spirit. The light fluid still consisted of particles which vibrate longitudinally in a ray. The fringe of colours produced as light passes through a small hole was due to the flow of light through a hole being slower near the edges and fastest in the centre. Each of these people did not hold their views in isolation but were characteristic of the views held by many of their contemporaries and those who came after.

61.5.2.4 Wave Theories

Huygens, in the mid seventeenth century, was one of the first to employ a wave model for light, even though the more detailed (and more often quoted) aspects of such theories were brought together in the beginning of the nineteenth century by Fresnel in particular. Sabra (1981) explained that Huygens was initially influenced by the work done by Descartes, and he attempted to “tackle difficulties in the Cartesian theory” (p. 199). He also drew on some of the ideas expressed by Hooke and Pardies, both of whom he specifically mentioned in his 1679 publication (Traité de la Lumière). This is not surprising as those two also were influenced by Descartes. Huygens’ work was by no means a complete theory of light as he neglected to discuss some phenomena which were known at the time. He drew a comparison between light and sound in terms of their properties, and similarly between waves in air and water. Sabra (1981) referred to Huygens’ description of the passage of light through the ether as resulting from the ether particles acting like rows of “contiguous and equal spheres” (p.211). Huygens proposed his well-known principle that, for any wave,
each point on the wave imparts some of its motion to all of the points around it. Sabra (1981) quoted from Huygens’ *Traité de la Lumièrem*, pointing out a significant, and new, aspect in his description of light, that being his assertion that, in relation to light waves,

the percussions at the centres of these waves possess no regular succession, (and) it must not be supposed that the waves follow one another at equal distances (p. 212).

This is clearly not just an abstract mathematical conceptualisation but is based on a description of how light is transmitted successively from particle to particle in the ether. Additionally and importantly, Huygens did not envisage the waves as being periodic.

The work of Huygens notwithstanding, the beginning of wave theory as a substantial and broadly applied description for light is generally set in the first twenty years of the nineteenth century. In current standard textbooks, particularly those written for secondary school physics, Young is suggested as the initiator of the wave theory but this may be better described as a ‘logical reconstruction’ of history - the double-slit experiment could be used (and often is) as the first practical illustration of an optical property which is only explainable by a wave conception of light.

During the second decade of the nineteenth century, Fresnel, an engineer with an interest in optical phenomena (as distinct from being purely a research scientist) became interested in diffraction and the possible explanations for it. He worked in relative isolation from other scientists in this regard, and in particular, during 1814, he was, according to Cantor (1983), “unaware of Young’s earlier discussion” of diffraction (p. 151). Wood (1954) suggested that the first time Fresnel became aware of any of Young’s work was late in 1815 when Arago showed him some of Young’s published papers. Initial attempts by both Young and Fresnel, in their respective countries, to explain diffraction were based on light which was reflected from the edge of the diffracting material causing an interference-like effect with the light which just passed by the edge. Eventually Fresnel drew up a theory to explain diffraction and many other known properties of light, such as polarisation and double refraction, working with a mathematical model based on algebra and calculus which took account of all points on a wavefront, as distinct from Young’s simpler geometric approach based on rays. Arago’s encouragement and a monetary prize offered by the Paris Academy resulted in Fresnel writing a paper which not only effectively
explained optical phenomena using a wave model but was also successful in actually winning the prize. Until then, French scientists had been unable to satisfactorily explain diffraction using a particle model and thought that the offer of a prize might stimulate others to resolve the matter. Although the panel had presumed a particle-based theory would be forthcoming, they eventually accepted the worth of Fresnel’s wave description to the extent that they used it to predict the existence of a central bright spot behind a circular shadow. When they found such a spot, the success of Fresnel’s work was assured. This is not to suggest, however, that the wave model was immediately accepted unequivocally by all scientists from that point in time. Debate continued in both England and France, sometimes with a degree of acrimony between participants, regarding the effectiveness of one or other of the two theories of light, particularly with regard to polarization. Those in France included Fresnel, Malus, Arago, Biot, Poisson and Ampere, while in England there were Young, Brewster, Herschel and Brougham. Even among the wave theorists, there were at least two groups – some favouring a ray description and others a continuous wave model (Buchwald, 1989).

6.5.3 Objections and Responses

Each of these theories of light not only had their proponents but also their critics. As in any community where there is a range of views, support for a particular standpoint is not limited to elaboration of those views but also includes attempts to expose weaknesses in the opponents’ views. The success of any particular theory depends not only on a demonstration of its own strengths but also of the flaws in the others. Since the beginning of the scientific revolution, there have been numerous instances of this competitiveness between various schools of thought, and between specific individual scientists, in the field of optics. This contributes to what many describe as the social construction of scientific knowledge. It has been discussed in general in Chapter 4 in relation to various frameworks including those described by Kuhn (1970), Barnes and Edge (1982), Collins (1985) and Woolgar (1988) among many others.

Descartes was one of the principal designers of the new scientific approach and he used the field of optics to illustrate how nature should be investigated (see section 7.3.7). His publication of *La Dioptrique* in 1637 initiated an early example of an on-going debate with Fermat. Sabra (1981) suggested that “the importance of the
controversy … can hardly be exaggerated” (p.85). Fermat doubted Descartes’ proof of the law of reflection. He similarly argued against the logic of Descartes’ derivation of the law of refraction, preferring to approach an explanation of the phenomenon using the metaphysical principle of least time. Sabra’s (1981) observation was that geometry and metaphysics joined forces in an attempt to defeat Descartes and his followers by going beyond mere opposition to their arguments and actually producing the true law of refraction (p. 136).

Fermat’s disagreement with the Cartesian approach was conveyed over a period of time to various mutual acquaintances such as Mersenne, Clerselier and Mydorge and these interchanges have been described in detail by Sabra (1981). Interestingly, it appears that the two principal protagonists in the debate, Descartes and Fermat, did not seem to have been in direct contact with each other but rather with various other third parties who forwarded comments by one to the other. Their paths first crossed as a result of Descartes sending an early copy of La Dioptrique to Mersenne for comment. Crombie (1957) referred to the latter as “the widely read mathematical commentator” (p. 280), and Ariotti (1975) accorded him an even more central role in science at the time, referring to him as “the correspondent of practically all men of science and philosophy in Europe in the first half of the seventeenth century” (p. 381). He distributed Descartes’ publication to others, Fermat included, to contribute to this task. Accordingly, this could be seen not only as a dispute between supporters of two differing theories, but also as an early instance of the peer review of a publication.

One of the most widely discussed confrontations between two scientists was that between Newton and Hooke. Their ongoing dispute began when Hooke, a respected member of the Royal Society, reviewed a paper submitted in 1672 by the younger Newton on the Theory of Colours. A new proposition (Newton’s paper in this instance) requires someone experienced in the field to examine it. Sabra (1981) explained that Hooke, in 1665, had already developed a theory of light in his Micrographia which was centred on the notion of a “pulse or motion” through a medium, somewhat after the view of Descartes. He, Hooke, was reluctant to accept a different interpretation, partly because his own theory could have adequately explained Newton’s observations and perhaps partly because of a reluctance to commend too readily the ideas of a younger, less experienced, less well known Newton, at the expense of his own theory. Newton wrote a set of Answers to the
Considerations which Hooke wrote with respect to Newton’s paper, but only the Answers were published and not the comments of the reviewer (Hooke). The situation illustrates the theory dependence of observations and knowledge construction: Hooke was unable to evaluate Newton’s paper except in the light of his own theory.

Apart from disagreements regarding the nature of light, another point of contention between these two related to colours. Newton had observed five (later seven), components of white light, whereas Hooke proposed that all colours could be produced from two - red and blue - or various dilutions and proportions of those two. In response, Newton was “led to propose a theory of selective absorption” (Sabra, 1981, p. 262) to explain how light passing through varying thicknesses of red and blue solutions could produce “new” colours.

Another of Newton’s critics was Pardies. He objected to Newton’s idea that the refrangibilities of different colours was necessarily related to a corpuscular description of light. He was concerned by the proposal which implied that a ray of white light could be composed of a large number of coloured rays.

In the early decades of the nineteenth century there was also much debate concerning an appropriate model for light. The wave model did not have a smooth passage of acceptance into scientific thinking, even after Fresnel’s admirable explanation of diffraction as a wave phenomenon. There was often heated argument between Arago and Biot in particular regarding particles and waves or concerning priority of discoveries related to chromatic polarization, with reputations and academic standings being as much the driving force behind such discussions as was a search for a successful model. Buchwald (1989) described Arago’s “debacle with Biot over priority” (p. 79) regarding chromatic polarization in 1812 and noted that

Arago felt Biot had successfully usurped his position as the exponent of a new field of optics just when he was about to make a particularly impressive contribution (p. 80).

In relation to Arago’s strong support of Fresnel a few years later, Buchwald asserted that there “was more at stake than an experimental discovery” (p. 80).

Despite Young’s work in England in the previous ten years, it appeared to have little influence in developments in France. In Frankel’s (1976) view it “was almost completely ignored” (p. 155). There may have been more to the lack of awareness of his work in France than meets the eye however. As Frankel pointed out,
in 1816 Biot wrote to Brewster summing up the French attitude to Young by indicating that he carried “no more weight … than … Aristotle” (p. 155) and that he (Biot) was unaware of Young’s theory. It appears that privately, however, there were some among the French who had read Young’s Lectures and Malus had even communicated with him in a complementary way regarding some aspects of his work.

In addition to the controversy surrounding optical developments in France, there was on-going debate with socio-political undertones occurring in England as well in the early decades of the nineteenth century. Notwithstanding Cantor’s (1983) analysis of four strands of thought regarding a description for light, Chen and Barker (1992) used “the dichotomy of the emission theory versus the undulatory theory” (p. 75), offering as their justification the views of the scientists of the time:

this was the way that the historical actors labeled themselves in Britain after the mid-1820s. Before this period or in France, the circumstances were different. (p. 75)

The highly regarded Brougham had established a sound reputation at an early age within The Royal Society for his optical researches and was influential in the lack of more ready acceptance of the undulatory ideas outlined by Young (a vibrationist in Cantor’s classification). Brewster was also a keen emissionist and well-respected in the Society, having been awarded Copley, Rumford and other medals during the 1810s and 1820s for his work in optics. He argued continually in favour of a particle theory and, as late as the 1840s, called on Brougham (who had, by then, been involved in government and the law for many years) to return to optics and the emissionist cause (Chen and Barker, 1992). Further reference is made to these developments later in the chapter in sections 7.5.8 and 7.5.11.

6.5.4 Communication

One of the most dramatic changes which could be seen in the way people investigated natural phenomena is related to the way they described their thoughts, observations and theory structures to others. Since the time of the ancient Greeks (as far as Western civilisation is concerned) there have been people who have developed and publicised their ideas about the principles which determined the way everything on the earth and in the heavens happened. Pythagoras, Aristotle and numerous others espoused their ideas in various schools and other types of institutions and societies. In some cases, particularly Aristotle, their ideas held sway within western and near-
eastern societies for centuries. This chapter is not so concerned with that earlier era, but rather with the years from about 1600 onward. As explained in section 7.3.4, much of what people did in relation to investigations of natural phenomena, immediately prior to and during the early years of the scientific revolution, was done on an individual basis. While there was some communication from one person to another, such discourse was slow to take place and so the shaping and reshaping of ideas was also slow. A significant factor in the determining whether a person will change their ideas is the depth and quality of challenge which is presented - communication is therefore a fundamental requirement to theory development, in addition to a culture in which ‘challenge’ is expected and provided. Communication within the institution of science has taken many forms which include: direct contact between two people either in person or via letter; group discussion in informal settings or formal societies; printed documents and papers written by society members and distributed within these formal societies; books; conferences and seminars drawing together people with a common interest.

Around 1600, a number of societies formed in Italy which enabled groups of people to meet regularly to discuss ideas ranging from the structure of the universe to the explanation of everyday phenomena. Although it did not endure, the Academia dei Lincei was thought by Ziman (1976) to be the first “properly constituted scientific society” formed in 1603, while Eamon and Paheau (1984) discussed the Accademia Segreta - “a sixteenth century Italian scientific society” as an even earlier society. The actual identity of the first society is of lesser importance, in this context, than is the time when such societies began and the role they played in scientific development from that time. By the middle of the 1600s the so-called Invisible College of people with a common interest in studying natural phenomena had begun to meet regularly, initially in the social setting of places such as coffee shops in London and, by the early 1660s had formed the Royal Society. Other societies soon sprang up both in England and in Europe, some being self-funded by membership subscriptions while others enjoyed some form of government or royal sponsorship (despite the implications of its name, the Royal Society was of the former type). These provided a forum for a range of new forms of communication beyond the private letter which had been the principal means of information and idea exchange until then.
Ziman (1976) described the ways in which the format of private letters changed within societies to the point that they were actually a public form of announcing a new development (for example Physical Review Letters) prior to a more detailed publication at a later stage. In addition to adding to the knowledge pool as quickly as possible, such letters also helped their authors in establishing priority in discovery. The same author also described the role and central importance of journals and books, and forms of verbal communication such as seminars and lectures, which are conducted usually within a particular theme and primarily for the benefit of scientists whose field of study is closely related to that theme, and public lectures which serve the purpose of bringing science to the public. This latter form of communication, while not directly related to the production of further scientific knowledge, has been an aspect of scientific communication since at least the early 1700s when attendance at, and an ability to discuss the themes of, such public lectures was a significant social activity among the middle classes. Indirectly such public communication, external to the institution of science, does have some indirect influence on the direction of the development of scientific knowledge, particularly of more recent times given the necessity of science funding from the public or corporate sectors of society and hence the necessity for an aware public. Ziman not only pointed out the importance of such communication with the public but also the difficulty in achieving it effectively.

Instances of communication between scientists involved in developments in optical theory during the seventeenth century have already been referred to elsewhere in this chapter (especially section 7.5.2). Examples include the more-or-less private communication between Descartes and Fermat (and others), and the somewhat more public discussions between Hooke and Newton. The latter example involved communication between the two men at the individual and personal level after Newton became involved in scientific communication at the more formal level - he had submitted a paper to the Royal Society regarding his views on the nature of coloured light. Others, including Huygens and Pardies, were involved in these discussions, each arguing different points of view in the evolution of a theory of colour. Details of these developments are recorded in numerous publications, including Shapiro (1980) and particularly Sabra (1981). For much of his life however, formal communication was not as integral to Newton’s scientific career as it has been for most other scientists. Although he was eager to ensure that recognition and
priority of discovery were correctly established (as seen in his on-going arguments with Hooke described by Fauvel, Flood, Shortland and Wilson (1988) the “most notorious of his disputes” (p. 19) and with Leibniz in relation to the development of the mathematics of Calculus, both situations illustrating his concern for recognition), he was not prepared to allow such issues to occupy his time unduly. When he became involved in almost intractable arguments with Hooke, in particular, regarding various aspects of optical theory, he refused to publish, in book form, any of his ideas about light until after Hooke died - a stance with which Park (1997) held some sympathy:

> It is not surprising, when each new word provoked fresh objections, that he gave up preparing his *Optical Lectures* for publication. (p.206)

The middle of the eighteenth century also provides an illustration of the extent of formal communication in optics and of the significance of the role it performed. Cantor (1983) referred to the “circulation … of works like those of Rohault and LeCat” (p. 117) and the impact such works had on British writers. At around the middle of that century Euler also provided communication which was important in publicising and clarifying the vibration theory, in specifying the problems he had with the projectile theory, and in responding to the arguments which had been published against the vibration theory. Cantor suggested that it was Euler’s *Nova theoria lucis et colorum* which was the principal publication used by projectile theorists who wished to comment on the vibration theory.

The role of communication in scientific theory development is complex, it occurs on many levels, and is largely dependent on advances in technology. Ziman (1976) recognised the importance of the invention of the printing press when he suggested that the “coincidence of the rise in science with the discovery of printing is not at all an accident” (p.”97). In addition, the significant increase in communication which occurred with the introduction of scientific societies was pivotal in the dramatic increase in development and change which took place in science from the later 1600s. Ben-Chaim (1998) discussed various styles of such formal communication between scientists during this era.

6.5.5 **Analogies, Models, Laws and Theories**

Throughout the various developments and debates about light during the last four centuries, the focus of the people involved has been at different levels. In explaining a particular observation or phenomenon, a scientist may make
comparisons with some other more familiar occurrence which may or may not provide a basis for more detailed study and prediction associated with the original phenomenon. In doing so, the scientist would be proposing an analogy, which has limited explanatory power. Descartes described his understanding of reflection and refraction by way of an analogy between the motion of light and that of a tennis ball. He was certainly not suggesting that light involved the motion of particles from one location to another because, elsewhere, he went to some lengths to discuss light as a vibration within the ether which transmitted a pressure wave from place to place. He also stated emphatically that the speed of light was infinite, a concept which was not consistent with particles but which he did understand as being possible for a pressure ‘wave’. The use of tennis balls in his discussion of reflection and refraction was, for Descartes, an analogy between the way two different phenomena behave without implying that the two were therefore equivalent. Sabra (1981) noted that Descartes formally recognised the “role of analogy in a purely deductive scheme of explanation” (p. 29). Ronchi (1970) referred to other comparisons he used in his discussions of light including the “blind man’s stick” (p. 114) in reference to the speed of light, and a “vat full of grapes” (p. 115) and a “jet of sand” (p. 116) to describe other aspects of light and the ether. Eastwood (1984) discussed in detail Descartes’ use of these analogies, referring to them as the “explicit building blocks for the models of direct, reflected and refracted light” (p. 160), while noting that Descartes recognised their limitations.

Another common analogy was that made between sound and light. Cantor (1983) described the efforts of LeCat, Euler and Young as prominent people who, among many others, found the comparison fruitful. He, Cantor, also noted that analogies have been used to illustrate, and hence support, more than one theory, as was the sound-light analogy for both the wave and vibration theories, this occurring partly because differences between the two “were not always clear-cut” (p. 190).

A law is a precise statement in relation to a specific set of circumstances or observations and is intended to be completely generalised whenever that situation arises and so is accurately predictive. The study of optics provides a number of examples of how laws are an integral part of the investigation of many phenomena. Various people throughout history from early times until the early seventeenth century had tried to ‘explain’ refraction in that they attempted to determine a pattern
in the way light changed direction when travelling from one material to another under a range of different conditions. Cohen and Drabkin (1958) described in some detail the early efforts of Ptolemy in the second century A.D. to determine a ‘law of refraction’ by careful angular measurement and mathematical analysis. As discussed in section 7.4.4, there were at least three people (Harriott, Snel and Descartes) who, in a relatively short period of time, developed a mathematical relationship for refraction, the form of which remains to this day. (The spelling of the Dutch name ‘Snel’ is often anglicised from the Latin form of the name – Snellius – but Park (1997) suggested that “Snel seems to be more authentic” (p. 68).

A model is proposed as a more literal description of the area of study in question. The notion of a model is closely related to that of a theory. Ziman (1978) discussed models in the physical sciences as ‘toys’ which the scientist played with in order to

(d)educe a number of quantitative and semi-quantitative features or behavioural properties that may perhaps appear similar to the observed properties of real systems (p.172).

Models are idealisations as are, for example, the ideal pendulum with its extremely ‘light bob’ on the end of an ‘inextensible string’ which is used to explain the properties of oscillating objects, or the perfect gas made of particles travelling at high speed at great distances apart and so on, or, similarly, the particles emitted from a light source as a basis for the emission theory of light. Lakatos (1970) considered models as the starting point for construction of a theory:

A ‘model’ is a set of initial conditions … which one knows is bound to be replaced during the further development of the programme (p. 136, his emphasis)

The scientist knows that the model will be changed by increasing its complexity to account for more observations. This does not necessarily mean that the changes are ad hoc as referred to above.

The broadest goal which a scientist might be striving for is the development of a complete theory which is a set of explanations encompassing all properties and experiences pertaining to a particular area of interest (for example, optics). The production of a successful theory description could be thought of as being at the highest level of understanding in relation to the analogy, model and theory, although they are not simply positions along a linear continuum of investigation within a
particular field. The provision of a successful description of a theory is therefore regarded highly and defended stoutly. A successful theory will, at the very least, account for all observations. It will be relatively simple. Chalmers (1976) suggested that it should be internally consistent and coherent, and will be held in less regard if it depends on ad hoc modifications to account for new observations. It may also suggest previously unseen properties or phenomena.

During the centuries of developments in optics there have been numerous situations illustrating each of these four structural features which occur in any area of scientific investigation.

Optical theories which have been developed were discussed in section 7.5.2. There were attempts by Newton, Huygens, Euler, Fresnel and many others who, to a greater or lesser extent, attempted to provide a theoretical framework which would enable all properties and behaviours of light to be explained. The degree of consistency and coherence within any optical theory was variable and certainly not complete, and this resulted in modifications being made. This could be seen for example when Newton needed to account for simultaneous reflection and refraction at a surface with his “fits of easy transmission and reflection” which he introduced, according to Sepper (1994), as “an ad hoc hypothesis incoherently tacked onto the theory” (p. 142). Modifications also occurred as a result of debates arising between interested parties. These debates were sometimes directly between two people such as Newton and Hooke, or emanating from one person and being directed towards a large group as in the case of Euler’s criticisms of the projectile theory in the mid-eighteenth century or Brewster’s and Brougham’s attempts, in the mid nineteenth century, to cast doubts on the undulatory theory.

6.5.6 The Speed of Light

Prior to the start of the seventeenth century, any discussion of the speed of light was associated more with philosophy than practical measurement. Even at the beginning of that century, Descartes had said that

(light) reaches our eyes from the luminous object in an instant; ... if it could be proved false, I should be ready to confess that I know absolutely nothing in philosophy (Sabra, 1981, p. 48, translated and quoted from a letter written by Descartes in 1634).
Whether light travelled with some speed or not was very much dependent on what the nature of light actually was. Some (for example Aristotle) considered that it was a “state or quality of the medium” (p. 263) as Zajonc (1993) described it, so that it either existed or it didn’t - the medium had the quality of either ‘darkness’ or ‘light’ - hence the notion of speed was irrelevant; others (for example, Descartes) thought it was a pressure wave in the ether and so was transmitted as the movement of one end of a stick simultaneously moves with the other end hence its speed would be instantaneous; for those who thought light was particulate, light would take some time to travel from point to point and so would have a finite speed. Whether light had a finite speed or not provided argument for proponents of the various models for light to further their cause or challenge and diminish others’. Descartes’ attempts to justify his position to Mersenne on the instantaneous transmission of light is one such example and was discussed by Cohen (1940).

Since the early seventeenth century when practical attempts were made to determine the speed of light, both the question of its speed and the method of measurement have had a significant impact not only on people’s understanding of the nature of light but also on the nature of the ether. In both cases, the result has been important philosophically as well as for pure science.

The first description of an attempt at practical measurement was given by Galileo who suggested that two people, each with a lantern, stand some distance apart and the second uncovers their lantern at the instant when they see the first uncover their lantern. The time lapse between the first person uncovering their lantern and seeing the light of the second lantern would give a means of calculating the speed of light. Cohen (1940) described how members of the Florentine Academy who attempted the measurement reported that “we tried it at a Miles distance … and could not observe any (time delay)” (p. 332-333). The first occasion when an answer based on observation appeared imminent was in 1676 when Roemer suggested a reason for the periodic time delay in the sighting of the eclipse of one of Jupiter’s moons during the course of a year. Without attempting a direct measurement of the speed of light as the Florentine Academy had done, Roemer proposed that the time delay might be due to the extra time required for the light from Jupiter’s moon to traverse earth’s orbit around the sun, and so inferring that the speed of light must be finite. Given the connection between light’s speed and people’s views about the nature of light
(especially Descartes’), such a suggestion was unlikely to be accepted readily. Roemer’s relative youth – Cohen (1940) referred to him as the “young assistant” (p. 340) to Picard (the latter being replaced later by Cassini) at the French observatory in the early 1670s – may also have been a factor in the lack of ready acceptance. Accordingly, it was some decades before the explanation had gained complete agreement, principally as a result of the work of Bradley according to Cohen (1940). In the meantime there was much discussion about the actual time delay in appearance of each of Jupiter’s moons after their eclipse, and hence for the time for light to travel from the sun to the earth. Cassini and Bradley in particular had determined times between seven and nine minutes. Others such as Newton and Halley, although not making direct measurements themselves, accepted the values published by others, especially the above two astronomers, in deference to their perceived skill in measurement. In addition to his focus on the timing of Jupiter’s moons, Boyer (1941) reported on the many others who had made various attempts to estimate a speed for light, if indeed it was finite.

Of some interest in relation to the first values for the speed of light is the apparent lack of agreement between contemporary scientists, and also between later historians, in the reporting of the actual value for the speed implied by Roemer’s proposal. Boyer (1941) pointed out that Roemer did not propose a definite value for the speed of light, beyond his introductory remark that light requires less than a second of time to traverse a distance … about equal to the diameter of the earth”. (p.27-28)

He, Roemer, was primarily interested in an accurate determination for the delay time for the appearance of Jupiter’s moons at different times of the year and inferring from those observations that light took some finite time to cross the earth’s orbit. Cohen (1940) suggested that “the emphasis in his paper was upon the fact of a mora luminis rather than upon the estimate of its value” (p. 29). This situation notwithstanding, many historians and others have “quoted” a figure purported to have been calculated by Roemer for the speed of light, and Boyer (1941) has listed some of the many different values quoted for this figure, along with some possible reasons for the variations in figures given.

During the eighteenth century those who had proposed one or other of the various models for light, especially Euler as discussed by Cantor (1983), often also
extended their mathematical analysis to include equations which provided a basis for a calculation of the speed of light. However because these depended on such unknown qualities as the elasticity and density of the ether, an actual determination was not possible. Nor was such mathematics amenable to determining the quantities related to the ether, even though estimates were made once a figure for the speed of light became acceptable, because the equations contained more than one unknown.

Which model of light was preferred actually depended on the speed of light in various media - a wave-based model could explain refraction if light was slower in glass or water than in air, but a particle model was required if the speed was greater in water or glass. Despite such a seemingly straightforward *experimentum crucis*, a method of determining speeds or even simply of comparing speeds was not forthcoming during the eighteenth century.

Direct measurements of the speed of light first achieved some success in the middle of the nineteenth century. Fizeau and Foucault, first in collaboration and then separately after a personal dispute, determined a relative value for the speed of light in air compared to water. During the 1850s at times together and later individually, they used a rotating mirror and split the reflected light beam so that part of it travelled through water and another part through air. Their efforts were described in detail by Jaffe (1977). This provided the clear-cut evidence required to establish the superiority of the wave theory over the emission theory (although the former theory had gained general acceptance by about 1840, the efforts of Brewster and Brougham, as described later in section 7.5.8, notwithstanding). Of equal importance was Fizeau’s later determination of the actual speed of light in air using similar apparatus. The significance of this work is greater from the twentieth century standpoint, however, than it may have been to Fizeau’s contemporaries. By 1850, it was not critical for the wave model to gain support from a physical test - the work of Fresnel and others with diffraction, polarisation, and other phenomena had provided sufficient argument to confirm the superiority of the wave theory. Fizeau’s measurements are more useful as part of a logical reconstruction of the development of theories of light than they were another nail in the coffin of the projectile theory at the time. Later work by Michelson and Morley, described by Jaffe (1977), not only confirmed these earlier result but also provided the basis for dismissing the notion of the ether as a medium for light,
although an examination of the details of that work is not necessary to achieve the purpose of this thesis.

6.5.7 Multiple Discovery

Analogies and models are tools which scientists use to help others to envisage the way a particular natural phenomenon can be interpreted. They clearly have a function but their development is not something which is highly prized by other scientists. Such is not the case for laws and theories. Both of these require some significant degree of intellectual input and so the recognition of the first person to develop a respectable law or theory gains status among their peers (and perhaps the wider society). It has happened often that a law or theory has been produced by more than one person independently, but this independence of discovery must be clearly established if each scientist is to gain the recognition they desire or deserve.

Explanations for the occurrence of multiple, or simultaneous, discovery are varied. Lamb and Easton (1984) suggested that they include metaphysical theories, statistical explanations (“the ripe apple theory”), sociological accounts and cultural progress. In the field of optics, the phenomenon was exemplified during the early seventeenth century with the development of a law of refraction. Shirley (1951) and Sabra (1981) make the point that Snel, Descartes and Harriott (Shirley referred to Harriott and “his friends Walter Warner and Sir Thomas Aylesbury”) had, at various time over three decades, described virtually the same law based on trigonometry, although it appears to be unclear, whether any of the three had worked together or exchanged ideas on the phenomenon. Park (1997) was prepared to recognise that Harriott was the “first to know how light is refracted” (p. 172). There was some importance given to priority of discovery, even at that time, as is indicated by Sabra’s reference to comments made by Isaac Vossius which suggested that Descartes had plagiarised the law from Snel. Sabra also detailed the lack of certainty in the sequence of events regarding the development of a law of refraction during the 1620s. Descartes, Snel, Huygens, Mydorge and Golius were each aware of the work of some of the others but it is unclear whether Descartes and Snel, in particular, were aware of what each other was doing in the area of refraction. Accordingly, Sabra retained an open mind on the question of multiple discovery versus plagiarism. All of this still leaves unexplained the work of Harriott who was reported to be involved in experiments related to refraction using glass prisms during the first decade of the
seventeenth century. (Snel’s document describing the law was written in 1626 and Descartes’ publication was in 1632). Shirley noted that

> It is not surprising that the English, the Dutch, and the French should all come to agreement on the laws of refraction: the study was a popular one and dozens of independent investigators must have been working on it simultaneously”. (p.508)

Resolution of issues relating to priority of discovery in relation to a law of refraction are made more difficult due to the lack of detailed records, particularly those of Harriott, as mentioned by Shirley (1951), and Snel, as indicated by Sabra (1981).

This situation not only provides an illustration of how a particular scientific law came about, but also a description of how scientific ‘discoveries’ do not occur in a clear-cut, sequential fashion. Because of widespread interest in a particular natural phenomenon, it is demonstrably likely that a number of people will arrive at an explanation at a similar time. In this instance, the time span is significant (some 30 years) but that is understandable for the era, that is, there were limited opportunities for worthwhile communication to occur. In turn, this says something about the importance which scientists may have placed on exchanging information for the betterment of science itself, as distinct from making observations and arriving at explanations purely for the satisfaction of the individual scientist. On the one hand, travel for the purpose of information and idea exchange was time-consuming in the extreme, and on the other, the desire for a widespread collection and consolidation of ideas had not developed at that time.

6.5.8 Theory Change

The common view of scientific theory development is based on a notion that, every so often, a scientist ‘discovers’ something and this provides a basis for review and change of scientific theory which replaces what came before in a smoothly continuous way. This description is often referred to as the “received view” and the underlying philosophy is termed “positivist” (see Chapter 4, especially section 4.5.2). Developments in the history of science suggest that scientific change (the term ‘progress’ presumes too much and is value-laden) follows a path which is anything but a simple move from one idea to the next with all scientists moving as one to the new idea. The actuality is that rarely does this occur, at least as far as the over-riding paradigms and major theories of science are concerned. At the day-to-day level,
within a particular paradigm, the ‘normal science’ as Kuhn (1970) called it (see Chapter 4, section 4.5.3) provides new information and data which supports the paradigm or are consistent with the ‘research programme’ concept of Lakatos (1970) and also discussed in Chapter 4 (section 4.5.3). But inevitably there are observations made which are inconsistent with the current theory framework. In isolation, these are disregarded for a variety of reasons including poor experimental technique or anomalous results which may have some explanation within the current paradigm but which is not immediately apparent. However such seemingly rational reasons to discount observations are not the only reason for their dismissal. The reputation of the scientist and the academic group he or she works with, or is supported by, are also factors which influence not just the significance which others place on results but also whether such results or observations are even publicised in journals, as explained by Collins (1975).

The field of optics illustrates the notion that change in science is not always smoothly continuous nor immediately complete. An outline of the variations in the different theories of light was described earlier in section 7.5.2 and reference was made to other historians who have provided more detailed studies of those changes and progressions. These all make it is clear that two (or more) theories can be relatively widespread and concurrent. The vibration, wave, fluid and projectile theories of the seventeenth century continued to attract varying degrees of support - particularly the wave and projectile theories - until the beginning of the nineteenth century. By then the fluid theory had few followers, and the vibration theory was on the wane. Cantor (1983) suggested that, by about 1830, the vibration theory eventually “merged with popular expositions of wave theory” (p. 205). Within each of these theories there were frequent fluctuations in the detail of their description as new phenomena were observed, fresh criticisms were mounted or debates between proponents of one or other theory arose, all of which prompted further refinements in or clarification of the theory. Any disagreement invariably was raised by followers of alternative theories. This was illustrated quite clearly in the on-going debate between Newton and Hooke. Gouk (1988) discussed the variations which Newton made to his theories as a result of his arguments with Hooke and she noted that “Hooke’s criticisms influenced Newton more radically than has generally been recognized” (p. 117).
Responses did not always focus on theory improvement - Newton provided modifications to the projectile theory to accommodate the newly-discovered phenomenon of diffraction in terms of attraction and repulsion of light particles in the regions very close to the edge of the object. In the mid 1700s, Euler enumerated a range of problems which were considered to be the main stumbling blocks at the time for the projectile theory including the transparency of solid objects, the loss of mass from the luminous object and others as summarised by Cantor (1983). In Euler’s case, not only did he raise objections to the projectile theory but he also attempted to answer some of the objections which had been raised against the vibration theory. One of these was the need for the vibration theory to have space filled with ether which would affect planetary motions, and the other was the lack of similarity between sound and light with respect to bending into the shadow region behind a barrier. The first of these was not so much explained as dismissed by Euler. He considered that the projectile theory fared no better as it also required space to be filled by matter - light particles. The second objection was based on an inappropriate comparison between light and sound - with sound, the vibration caused the actual material of the barrier was made to vibrate by the sound and so provided a mechanism for explaining the presence of sound in the shadow region.

During the three centuries from the early 1600s to the mid 1800s there was no complete agreement on what light was, with at least two, if not more, theories being current at any one time. Chen and Barker (1992) referred to the “emission-undulatory controversy” (their justification for that terminology was described earlier on page 225) between many scientists around Britain during the early decades of the nineteenth century. Despite the fact that Young was Foreign Secretary of the Royal Society at the time, little credit could be accorded his efforts to provide British scientists with an unbiased commentary of Fresnel’s work. Cantor (1983) noted Young’s “cryptic comments intended to downplay the innovatory nature of Fresnel’s work and to further his own claims to priority” (p. 162).

In addition to Young’s lack of enthusiasm for any acclaim which Fresnel might have deserved, Brewster and Brougham actively conspired to find ways to circumvent or disprove various aspects of the wave theory by designing experiments which would demonstrate new phenomena incompatible with the latter theory. Much of their investigations involved the use of two or three objects with straight edges and
which were placed at various distances between a light source and a screen, with the edges being on alternate sides of the light beam. They examined the diffraction-like patterns produced when a third edge approached the light beam which passed through the narrow gap created by the other two edges. Their idea was to create a difficult, if not impossible, challenge for the undulationists - it may have performed a similar role for the particle theorists like themselves!

Activities such as these on various fronts in the years around 1850 illustrated the need for a less widely known scientist (such as Brewster) to work with (even manipulating, in the case of Brewster) a more senior person (the elderly Brougham) who had some standing and respect within The Royal Society. Social and political concerns were almost more important than the rational science. Chen and Barker (1992) referred to Brewster’s “strategy” in trying to sustain the debate and they concluded that

he subordinated his cognitive goals to social concerns: who held the power was more important than how the experiments turned out (p.98)

Eventually their (Brewster’s and Brougham’s) efforts faded because of lack of mutual support and a lack of interest in their contributions on the part of the undulationists. This represented the last attempt to maintain an emission theory of light and, in the end, it died because of a lack of enthusiasm and interest on both sides, the age of Brougham (then over 70 years old) probably being a relevant factor also.

Clearly there were not just two clearly defined and separate wave and particle theories which coexisted until a crucial demonstration of light interference in the early 1800s, even though this is the scenario which is often depicted in the ‘standard’ textbook elaboration of events. There was sufficient variation in theory descriptions to suggest that there were more than two theories, each undergoing frequent modification in the light of new evidence or strong criticism, and the demise of the emission theory was not swift subsequent to Young’s interference work (projectile theories were enjoying a high point in acceptance around this time) nor after Fresnel’s more complete mathematical description of wave optics in the early 1820s.

6.5.9 The Changing Role of Experimentation

Throughout history, the nature and purpose of experimenting has not always been the same. In a very general sense, experimentation can refer to any activity
which involves a person observing or attempting to alter some aspect of their environment. Baconian principles enunciated during the early decades of the seventeenth century advocated a systematic experimental procedure whereby careful observations were made as a precursor to the formation of a general statement being made inductively. Henry (1997) described “Bacon’s method of gathering of empirical facts and setting them down in ‘Tables of Instances’” (p. 53). In earlier times, a systematic experimental philosophy was seen as almost counter-productive to knowledge generation because the properties of all forms of matter were connected to its inner qualities and the way those qualities interacted with the immediate environment. Any experimental investigation which was based on manipulation of the environment would, in effect, change what was being observed (a view which is not at odds with twentieth century quantum theory, although the earlier view is based on a different conceptual framework). Grant (1996) explained the irrelevance of experiments as follows:

controlled experiments would do little good, because they would interfere with the regular environment of any given substance and thereby prevent us from learning about its true nature. Experiments that did not interfere with the environment of a substance would consequently provide no more information than could be obtained by observing its natural operation. (p. 160)

A somewhat less dogmatic view of the role and use of experimentation was described by Boyer (1987) in recalling that “Galen in ancient times had distinguished between the via experimenti and the via rationis” (p. 111), although he, Boyer, nevertheless accepted that experimentation was not “one of the pronounced characteristics of the Middle Ages” (p. 111).

During the middle of the sixteenth century a change in this view of experimentation began to appear. Members of one of the first scientific societies - the Accademia Segreta in Italy - began to view experimentation differently. By that time, many procedures and techniques had been developed to produce a wide range of effects (especially medical and physiological cures) and their continued application was based largely on tradition, the occult and magic. The members of this society decided to test these ‘recipes’ by practical investigation and, if the supposed result could be obtained on three occasions, the recipe was ‘proved’. Eamon and Paheau (1984) recognised this as the beginnings of a change in approach:
Although the method employed here was obviously primitive, it is historically significant, for it reveals a stage in the development of the concept of experiment that stands midway between the medieval concept of experimenta as ordinary experience and Galileo’s method of using an experiment to test an hypothesis. (p. 333)

Not only could this development be seen in the way described by Eamon and Paheau as a change in the role of experimentation, but it also indicated a significant philosophical move away from the ‘matter-environment’ relationship described above.

These different roles of experimentation can be illustrated in the field of optics over the centuries. While discussing medieval attempts to explain the cause of the rainbow, Boyer (1987) lamented that

The typical catch-all explanations of the time show how desperate was the need for crucial experiments in the story of the rainbow. (p. 107)

Such an observation reflects an expectation that the way science was done during the Middle Ages is the same as it is now, that is, rainbows may have been explained more clearly if the right sort of “crucial experiments” were performed. However in those times, the concept of experimentation was not the same as in later centuries. So it was not simply that the “right” experiments were not designed, but that the conceptual framework did not exist at that time for people to even consider designing experiments to “test a hypothesis”, for example, as it has been done in more recent years, particularly since Bacon and Newton (his so-called “experimentum crucis”) for example. The role of experiment in science – the way in which people have interacted with the natural world in an attempt to describe and understand it - has not always been the same as it is now.

6.5.10 Science and Belief

Despite the logical objectivity which seems to form the basis of acceptance of new theories or approaches in science, closer analysis suggests that ‘belief’, of one type or another, often forms the basis of what is regarded as acceptable at any time. Silver (1998) suggested that “objective facts” are not the only things which influence science and he equated belief to “metaphysical reflections, religious faith, (and) scientific dogma” (p. 103). Directly or indirectly, these things influenced what a scientist did and the science which was produced.
Illustrations of the significance of belief can be seen in the history of optics. Descartes believed so strongly that the speed of light was infinite that he was prepared to stake his whole philosophy on the notion (see earlier section 7.5.6). Although he arrived at that position by ‘rational argument’ within his philosophy of the world, it was nevertheless an idea which was not based on any physical observation, it was a ‘belief’ of his and formed a central part of his optical theory. This belief was of the type which was able to be demonstrated in practice sooner or later, even though for Descartes it was more of a philosophical principle than an observable fact. Galileo regarded the speed of light differently - at about the same time that Descartes was expounding his view on the significance of the speed of light, Galileo was trying to actually measure it using lanterns situated on two hills as described earlier in section 7.5.6.

Another instance of this type of belief can be seen in Goethe’s approach to his development of an understanding of light. Duck (1997) observed that, throughout his life, Goethe steadfastly held to

his belief that light is immutable and that colours result from the interaction of light and darkness. (p.397)

This belief was held despite what Duck (1997) claimed was the evidence, presented by experiments which had even been performed by Goethe himself, which would “clearly demonstrate that light is composite and contains within it coloured lights” (p. 406). In repeating many of the experiments which Newton carried out, Goethe was able to provide alternative explanations for certain phenomena – explanations which were reminiscent of the Aristotelian view that colours arose from various mixtures of light and darkness. For instance he did not see a coloured spectrum when a white surface was viewed through a prism; colours only appeared near the edge of an opaque object placed so as to mask the view of part of the white surface. In Goethe’s mind, the immutability of light was intimately connected to his “unshakable pantheistic belief that light is inseparably bound up with God” (p. 406) and that light was “something spiritual” (p.405).

This suggests another form of ‘belief’ which underlies the construction of scientific knowledge. The notion of a paradigm as explained by Kuhn, and first discussed in this thesis in Chapter 4, could be applied to Goethe’s “pantheism”, as Duck described it. This form of ‘belief’ may imply a more conscious acceptance than
might be the case with paradigms, but both concepts involve a primary axiomatic framework within which subsequent research is undertaken and explained. Another example of such a belief is provided by the common view of the nature of light in the eighteenth century. Euler and other vibrationists notwithstanding, Newton’s corpuscular theory of optics was regarded as the basis of explanations of optical phenomena during much of that period. Dobbs and Jacob (1998) indicated the strength of his influence in the title of their publication (*The Culture of Newtonianism*) and Cantor (1983) referred to the “Institutionalisation of the projectile theory” (p.42). This deliberate following of Newton’s corpuscular optics during the 1700s could be an example of a belief which scientists and others had at the time. Newton had been so successful with his explanations of so many aspects of the universe that his views on optics were not only adopted and accepted by scientists at the time but were also distributed to the wider public via what was virtually a ‘social lecture circuit’. It had become the accepted practice for well-to-do people to display some interest in scientific matters and to be able to involve themselves in discussion of such matters at social gatherings. An understanding of the reason for the dominance of projectile optics during the eighteenth century needs to be seen in terms of Newton’s reputation and the widespread belief in his natural philosophy which followed from that.

There is also the form of belief which shapes the construction of a scientific theory. Cantor (1975) explained that

Fresnel believed that nature is basically simple, producing the maximum number of effects by the minimum number of causes; accordingly the scientist must aim to represent nature by employing the minimum number of hypotheses … (p.117)

It was this view which caused Fresnel to reject the Newtonian corpuscular theory for what he regarded as its arbitrary hypotheses which were introduced to explain new phenomena. He preferred the “simplicity and consistency” of his own mathematical wave theory. Fresnel’s optical theory was based on his belief in the way natural phenomena should be explained.

Newton’s early studies of the colours of light provide another illustration of how beliefs are a significant part of the construction of scientific knowledge. When Newton was investigating the dispersion of light as it passed through a prism, he described the colours which he saw. Initially, in the first of his series of *Optical
Lectures which were written in the early 1670s, he described five colours and made the comparison with the colours of the rainbow. Later, in the eleventh lecture, he referred to seven colours. In questioning the basis for the change, Topper (1990) suggested that there must have been some reason other than ‘that’s how many Newton really saw’ – such an explanation begs the question ‘why did he originally see five?’. Topper thought that the idea expressed by others who saw a connection between light and Newton’s interest in music and in the harmony in nature as being more reasonable explanation. But Topper proposed a further possibility – one based on Newton’s detailed examination of the spectrum in which he referred to the ‘extra’ colours (indigo and orange) as being the boundaries between other colours. This was done after quantitative measurements were made of the relative sizes of each coloured region. The inclusion of boundary colours gave a more even distribution of sizes across the whole spectrum. Quoting from Optical Lectures, Topper (1990) recalled Newton’s references to seven colours as being “more elegantly proportioned” and offering a “more refined symmetry” (p. 273). In other words, Topper concluded,

Newton’s shift seems to be a clear case of aesthetic factors dictating the structure of a theory (p. 273, Topper’s emphasis).

Recognising the complexity of the question and the multiplicity of possible explanations, Topper also noted Newton’s own analogy between the colours of the spectrum and the octave of notes produced on a stretched string. Newton’s understanding of musical scales was only beginning at that time also however, and so it may not have been so much an analogy between light and sound as a recognition of commonalities in two separate natural phenomena. Thus he perhaps saw an opportunity to draw the two fields of study together into a more unified theory after he had included the notion of the boundary colours. The result was a raising of the ‘status’ of the boundary colours to the equal of the other five. Topper finally concluded that Newton’s eminence was the reason why his “theory-laden perception of seven colours” has been accepted almost universally ever since.

‘Belief’, in the sense of acceptance of the reliability of the work carried out and reported by a scientist, is also an essential part of scientific progress to the extent that the latter could not occur without that type of belief. While a scientist will frequently check on the work of another to verify reported results, there comes a point where all scientists will believe and accept the work first reported by another without
every scientist having to check it for themselves - clearly the practicalities of doing that would mean that science would not progress at all. The degree of immediacy of acceptance depends on the reputation of the scientist, as suggested above in the case of Newton and the projectile theory, although the point is made here with reference to specific experimental results rather than the construction of a theory. In the late nineteenth century, Michelson performed extensive and carefully constructed experiments to determine the speed of light through the ether (see section 7.5.6). It did not require every scientist to repeat those measurements for each of them to accept that the ether was no longer a concept which needed to be part of an explanation of the motion of light. Light could exist without there being a medium to support it or, more fundamentally, light was not a particular property or state of a medium but was a separate phenomenon. Michelson’s experimental results were believed and scientists gradually began to redesign their description of the universe as a result of that belief.

6.5.11 Scientific Reputations

When a scientific observation is made and reported on or when a new theory is proposed or when a different technique is developed by a scientist its acceptance depends on the person who did the work. The standing of scientists among their peers is something which is recognised and valued in both formal and informal ways, just as it is in other fields of endeavour within a society. This reputation is what plays a significant part in determining whether the work of a scientist is believed and accepted or not. This is not necessarily in accord with the objective positivist view of science whereby whatever is undertaken or proposed by a scientist is not dependent on the person reporting the work or making the proposal.

Examples of the significance of reputation were referred to in the previous section in relation to Newton and the ‘Culture of Newtonianism’. At other times over recent centuries, the field of optics provides examples of the importance of a person’s reputation and maturity within the field. The final years of the projectile theory in the 1840s were outlined in sections 7.5.3 and 7.5.8 with respect to the debates involving Brewster, Brougham and members of the Royal Society. Brewster was the driving force behind the continuance of the debates but realised that his arguments would only carry weight if he had the support of a person of eminence within the field and so he called on Brougham for that backing. Frankel (1976) referred to Brougham as
“a leading British corpuscularian” in the early 1800s. Although the latter had not done any recent work in the field for some time (he was in his late sixties when Brewster contacted him) he had widespread respect among scientists who were involved in optical studies at that time because of his earlier work.

6.6 Conclusion

The foregoing analysis highlights a range of features of science which characterise its rich complexity and provide a contrast to the sterile picture which is often portrayed in standard texts and courses. The same sort of analysis is possible for any area of science which is relevant to secondary school science. There is no logical starting or finishing point for such a study because it should not be seen as a chronological roll-out of events which occurred throughout any particular period of history. The essential focus of an examination of the history of science should be the selection of instances which illustrate the processes and characteristics of science so that it is shown as an attempt by people to come to a consensual understanding of how to explain the nature of the universe.

One of the necessary requirements to gaining a full appreciation of the history is an understanding of the central theoretical concepts. To that extent, a study of science through its history incorporates the content aspect of standard science courses (albeit from a different perspective) within a wider study. Not only does an historical perspective require conceptual understanding but also involves an appreciation of a wider range of issues as well. Consequently, an approach to the study of science at secondary school such as that which is advocated by this thesis would require a greater commitment of class time than would be currently allocated for a study of the same area of science covered by traditional curriculum approaches.

The following chapter demonstrates how such a curriculum could be developed for a unit which centres on an understanding of optics. The framework employed there could be applied equally as well to any other area of study within science provided that appropriate historical research is undertaken.

REFERENCES


CHAPTER

7

A CURRICULUM DESIGN EXEMPLAR

7.1 Introduction

The central question directing this research concerns the attainment of scientific literacy by using history of science as a vehicle for teaching an otherwise traditional physics course. The variations in meaning of the concepts of scientific literacy, in particular the more recent (1980s and 1990s) definitions of the term, were examined in chapter 3. Chapter 4 was concerned with an overview of the significant paradigms and related issues associated with an analysis of the nature of science. The discussion in chapter 5 linked these two earlier chapters by proposing that an understanding of the nature of science was essential to the attainment of scientific literacy, and the nature of science could only be demonstrated through a study of the history of science. However the thesis is not about teaching a new subject akin to a history and philosophy of science course. The approach is that the curriculum framework should be based on a study of the historical development of one or a set of concepts within a traditional physics topic, and so this will inevitably result in opportunities to illustrate the characteristics of science without the need for a formal History of Science course. If an understanding of the historical development is absent, there will be no awareness of the characteristics of science and therefore no attainment of scientific literacy.

A model for curriculum design was presented in chapter 6, based essentially on Lawton’s cultural analysis framework. Chapter 7 outlined, in some considerable detail, significant aspects in the development of our understanding of the properties of light. Principally, many events, debates and personalities between 1600 and 1850 were examined as a background for the teaching of optics using the historical approach proposed in this thesis. The era is not important in terms of the approach, but that period of time does provide ample opportunities to illustrate the characteristics of science.

Lawton said an educational curriculum should be based on a study of the culture of a society. This should be undertaken by an analysis which was based on what he termed ‘Cultural Universals’ (see Chapter 6, sections 6.4 and 6.5). He
suggested that there might be nine of these and illustrated them by examining a western society such as England. In personal correspondence (see Chapter 6, section 6.5) Lawton indicated that the number of these “invariants” was not important or fixed. His “nine systems” or a similar set may therefore form the framework for a set of characteristics which might also describe the society of science. Accordingly, this approach was applied, in Chapter 6, to the institute of science to produce a set of “Dimensions of Science” (see section 6.6), based on the characteristics of science as outlined in Chapter 4.

The current chapter draws together the curriculum design features of Chapter 6 and the history of optics from Chapter 7 to illustrate the design of a curriculum plan in physics. It is accepted that the concepts which are currently described in the syllabus outline for such courses are still an important component of a science program, but it is proposed that they should be encountered as a result of studying the history of the developments of those concepts rather than being covered via some other perspective. The approach most commonly encountered is characterised in textbooks by a formal cognitive structure, an implication of objectivity in knowledge production and an abstract form of presentation and conceptual development. Where there is any attempt at historical treatment, there are often errors, omissions or unnecessary over-simplifications in the description of people and events. Such limited occurrences of historical treatment in texts are perhaps understandable given that they are often written to match a syllabus which has been specified by a state or regional educational authority. Consequently the primary sources of concern for the text writers and publishers are these course descriptions which place little emphasis, beyond the superficial, on the history or nature of science.

The last stage in curriculum development covered by this research is to illustrate how the cultural analysis approach modified from Lawton can be applied to a specific topic in physics. What follows in this chapter is an indication of how an optics course could be developed so as to incorporate traditional conceptual content but covered in such a way as to highlight the characteristics of science as discussed above. The concept areas which are commonly encountered in a typical secondary school curriculum in optics include the following: (i) Reflection and Refraction; (ii) Telescopes and other optical instruments; (iii) Particles and Waves (in the seventeenth century); (iv) Light and Colour; (v) Interference and Diffraction
(Particles and Waves in the nineteenth century); and (vi) the Speed of Light. The grid (Figure 8-1) shows which of the systems of science could be illustrated in each of

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**Figure 8-1**

*The Dimensions of Science in Optics History*

these areas. Ticks in the table indicate which aspects are commented on during the remainder of the chapter to illustrate how the framework can be applied. The table is intended to be illustrative rather than definitive. Many aspects associated with the development of an understanding in optics could be used to illustrate any of the characteristics. The following discussion is intended as an illustration to show that it is possible to design a physics topic so as to cover the range of systems of science across a traditional topic outline. It is expected that a study of the historical development of any other sub-discipline of science will enable a similar analysis matrix to be produced as the basis for curriculum development.

### 7.2 Refraction

#### 7.2.1 Knowledge Framework

The processes associated with knowledge production were described in Chapter 4 (sections 4.10.1 and 4.10.2). There is much in the seventeenth century development of an understanding of refraction which can illustrate these processes.
Natural philosophers had known of the phenomenon of refraction for hundreds of years before the seventeenth century. Many had tried to investigate it quantitatively to produce a mathematical relationship between angles of incidence and refraction, Ptolemy’s efforts being an early example (see Chapter 7, sections 7.5.1 and 7.5.5). The first thirty years of the seventeenth century finally saw the development of such a relationship by three different people: Harriott, Snel and Descartes. Kepler was also keenly interested in arriving at a mathematical relationship although the one he produced was not entirely accurate for all angles. Harriott and Kepler maintained correspondence through which they exchanged details of their experimental investigations in this area (in passing, this also illustrates the role of the communications dimension as part of the scientific enterprise). For a law of refraction to be regarded as acceptable, it needed to be consistent with all known observations and these needed to be known as accurately as possible. Practical observation and measurement, such as that carried out by Kepler in particular, were important for theory development. Harriott eventually produced the sine relationship based on these investigations. These developments have been described in Chapter 7 (section 7.5.7).

During the early 1600s, Bacon and Descartes separately defined how an investigation should be conducted and therefore how a knowledge framework should be constructed (see Chapter 7, section 7.3.7), although each had a significantly different perspective on this. Bacon based his approach on the derivation of knowledge from practical and systematically arranged observation. Whereas Descartes based his development of knowledge on a logical analysis of what was already known, and illustrated that approach by arriving at essentially the same result for refraction as Harriott, but by logical analysis of the tennis ball analogy which he devised (see Chapter 7, section 7.5.5). This contrasted with the method of Harriott who adopted more of an investigative approach.

Apparently independently of Descartes and Harriott, Snel also developed a mathematical basis for the explanation of refraction, and he became the source of the eponymous title of the well-known rule. In each case the explanation was in the form of a precisely defined relationship which enabled a prediction of the extent of refraction in any specified set of circumstances; the knowledge produced was essentially a ‘what’ rather than a ‘how’ or ‘why’ of refraction.
7.2.2 The Communication Dimension

Communication played a central role in Descartes’ refinement of his explanation of refraction with respect to his continuing letter exchanges with Fermat (and others) mostly via Mersenne as the intermediary ‘post office’. The same series of communications enabled the refinement of the alternative approach developed by Fermat based on what he referred to as the ‘principle of least time’ (see Chapter 7, section 7.5.3).

7.2.3 External Connections

Technology

To the extent that Harriott’s work was based on his experimental observations, a technology dimension was integral to the development of this area of optics. Reliable practical measurements were only made possible by the production and use of carefully manufactured materials, particularly in this instance, the glass prisms used in Harriott’s investigations as explained further in Chapter 7 (section 7.5.7).

Mathematics

A study of refraction may involve investigating and hypothesising on its causes, or measuring its effects or determining some means of predicting its effects. While some of these activities are descriptive, much is also quantitative and, to this extent, automatically involves the application of mathematics. Historically, the development of a mathematical description of refraction was therefore dependent on progress in mathematics. In particular, attempts to quantify the relationship between angles of incidence and refraction were necessarily limited to the range of known mathematical functions extant at any time. While Ptolemy had examined the feasibility of a quadratic relationship, he was not able to express it in a form which would be recognisable as such today because the use of literal symbolism had not been developed at that time (see Chapter 7, section 7.5.1). Similarly, a trigonometric expression of a refraction law was not possible until the corresponding mathematics had been produced. While on the one hand this could be regarded as simply stating the obvious, its significance is that it illustrates the notion that scientific progress cannot occur unaided and independent of progress in other areas. Scientific knowledge is not produced automatically or logically from a set of observations of some particular phenomenon in the natural world.
7.3 The Telescope

7.3.1 The Resource Dimension

The processes associated with funding in science can be examined as part of this discussion on the telescope, although it could also be done in many other sections. The ways in which financial arrangements are encountered at the individual and institutional level are important in understanding how the general operation of the scientific enterprise is sustained. The fact that funding is required at various levels is an important aspect of a broad and socially responsible science education curriculum. A scientifically literate society will appreciate the importance of a financial structure to ensure the effectiveness and productivity of the institute of science.

The financial dimension highlights the people who produce the scientific knowledge in addition financial considerations on the larger scale. During the 1660s when new developments in the telescope were being discussed, there is an opportunity to examine how people like Newton, Hooke and others were employed and by whom. This was discussed in Chapter 7 (section 7.3.4) as part of an examination of the lifestyles and daily activities of the people who lived during the era in question.

Hooke’s employment, firstly by Boyle and then by the Royal Society, Newton’s position as a professor at Cambridge University, Huygens’ work on the telescope while holding a position in the Académie Royale des Sciences in France all provide different examples of how a scientist was able to make a livelihood from science. Others, such as Boyle, were members of a class of society which did not need to seek paid employment.

At the institutional level, funding is illustrated by the organisations referred to above: the Royal Society and the Académie Royale des Sciences. Membership of the society involved annual fees and, as the name implies, the King also provided financial support because of his personal interest in natural phenomena and the work of the Society. This enabled scientists such as Hooke to be employed. The French Académie was similarly supported by King Louis XIV thus providing work for Huygens and many others. An awareness of such a money trail is valuable in seeing that the institution of science cannot operate at the level it does without external funding.
This is not to suggest that the only motivation within science is a monetary one. Reference has been made earlier (Chapter 4, section 4.9.1) to the various forms of reward which scientists receive. These may be formal, such as the peer approval which resulted in Newton being accepted as a Fellow of the Royal Society for his design of a reflecting telescope. But there is also the more personal satisfaction which comes from achievement, especially when that achievement is recognised by others. This was clearly illustrated, principally in a negative sense, in the disputes between Newton and Hooke regarding priority and independence of discovery in matters related to telescope design, as was discussed in Chapter 7 (sections 7.3.4 and 7.4).

7.3.2 The Communication Dimension

The significance and importance of a communication system within science could be considered during the Galileo affair in a negative sense as well as the positive. Certainly Galileo was involved in formal publications of books, letter writing to individuals and holding public discussions. But also the most significant aspect of the punishment which the Church handed out to Galileo was that he was not able to publicly communicate his ideas to anyone else or to further publish any of his views.

The telescope was also central to developments in optics during the later decades of the seventeenth century during the formative years of the Royal Society. In Newton’s attempts to become a member of the Society he first made contact through his design of a telescope based on a reflecting rather than refracting principle. This stimulated much communication between Newton and others involved in the Society, particularly Oldenberg (the secretary of the Society), Hooke and, from abroad, Huygens. This communication was the beginning of the angst which persisted between Newton and Hooke and Huygens over the ensuing years. Here was another example of the negative side of public communication although it was self-imposed in Newton’s case as he refused to acquiesce to Hooke’s demands for adequate recognition of the latter’s work.

7.3.3 Underlying Beliefs

Among scientists themselves, there was a reluctance to adopt Galileo’s ideas. This was partly due to the lifelong commitment they had already made to developing and explaining a geocentric system and partly due to the fear of retribution from the
Church (see section 8.3.4 following). In addition, because scientists were also churchgoers, their scientific work was influenced by their personal religious beliefs. The challenge to this cosmological paradigm was initiated by the telescope and Galileo’s creative use of it. Their commitment and beliefs were so strong that many refused to even look through Galileo’s telescope, claiming that whatever might be seen through it could be explained by imperfections in the glass lenses or other artifacts of the apparatus. Often these underlying beliefs within science operate as a barrier to further developments, so strong is the unquestioning acceptance of a theory or observation which had been a central part of the scientific knowledge structure for so long.

7.3.4 External Connections

Societal Influences

The telescope is one of the optical instruments which are often studied in a secondary school physics course. Galileo used the telescope to view objects in the sky, particularly the phases of Venus, detailed features of earth’s moon, the motions of the moons of Jupiter and the apparent motion of sunspots, all of which formed the basis of evidence supporting a non-geocentric universe. For centuries, the Church had described and decreed the way the objects in the visible universe moved and the hierarchical relationship they had with each other; it had also exercised domination in a political and secular sense over the general population in Europe (see chapter 7 section 7.3.3). The Aristotelian tradition was at one with the religious view that there were two different types of motion – one related to earth-bound objects and another for the heavens. The emergence of a cosmology which contradicted that of the Church and Aristotle and which could produce evidence to support its claims was therefore a threat to the continuation of its power and the traditional understanding of motion. The Church took steps to minimise (or even eliminate) any source of destabilisation of its reign, and scientists were equally reluctant to readily adopt such a change in what they had accepted as fundamental principles.

The affair was not simply a science versus religion debate. It also highlighted issues related to personalities and individual struggles for power. In this sense, the ‘social’ aspect of the socio-political system can be illustrated at the personal level as well as the institutional.

Technology
The “External Connections” dimension of science provides an opportunity to examine the relationships which exist between two or more different areas of science and the way in which one is able, either directly or indirectly, to provide a means of advance for the other. This can be illustrated during a study of the optics associated with the telescope by examining how the technology of spectacle-making, the science of astronomy and the study of optics were interdependent. The development of the telescope is thought to have been most likely prompted by a serendipitous event involving a pair of spectacles (see Chapter 7, section 7.3.6). The development of this optical device enabled advances in the study of astronomy (and, even more fundamentally, in cosmology). Then attempts to improve the performance of telescopes to further an understanding of astronomy provided a basis for greater understanding of optical phenomena such as spherical and chromatic aberration which, in turn, enabled advances in telescope design.

7.4 Particles and Waves in the Seventeenth Century

7.4.1 The Organisational Dimension

The discussion in the previous section surrounding Hooke and Newton also exemplifies the significant role which a scientist’s reputation has in the acceptance of his or her ideas. Within science, as with other sections of society, there is an expectation that an apprenticeship must be served before one’s contributions are given as much respect as those of the more mature members of science. One of the reasons why Newton’s ideas about the nature of light was not immediately accepted was due to his youth and relative anonymity. Hooke, on the other hand, had a long-standing reputation among members of the Royal Society (hence his task of reviewing the younger Newton’s work). There were, and often still are, more factors operating to determine the acceptance of a new scientific idea than its intrinsic worth.

Later, during the eighteenth century, it was just this situation which supported Newton’s ideas, almost without question. It was eventually the logic and power of his arguments and analysis contributed over a period of time which gained him his widespread reputation. As a result of the significance of the contributions he had made to science over decades, his mature standing within science made it difficult for other ideas contrary to Newton’s to gain a foothold.
7.4.2 The Resource Dimension

Within the developments surrounding the evolution of particle, wave and other theories there is a clear opportunity to examine the importance which scientists attach to rewards derived from the work they do. There are many forms which these rewards take and these forms have changed over the centuries, but one which has endured is that of priority of recognition for discovery, that is, for being the first to announce a new theory, viewpoint or interpretation. These features of science in action were discussed in Chapter 4 (section 4.9.1), particularly with reference to the contributions made by Merton. In so many situations involving progress in optics during the seventeenth century, Newton and Hooke took central roles. As pointed out in Chapter 7 (section 7.3.4), Hooke was the elder and hence more widely respected natural philosopher compared to Newton in the 1660s. During that decade, Hooke was a central figure in the establishment of the Royal Society and had important duties to perform in its early years. In the same period, Newton was progressing through his university studies, gaining a first appointment at Cambridge University, retreating to Woolsthorpe during the plague years, and eventually returning to university to take up a role as a professor of mathematics which required him to undertake a series of lectures. When he submitted letters and other forms of written publication to the Society (through its secretary Henry Oldenburg), the worth of his contributions was given to Hooke to judge. Given the latter’s prior interest and work in optics, his appointment as reviewer was understandable. His subsequent response to a paper by someone who proposed an idea which he saw as being similar to his own received the expected response of a person who would claim priority, and, where Newton’s ideas were different from his own, Hooke claimed that such new approaches were unnecessary extensions or complications, when his own theory had already incorporated the same phenomena with equal or less complexity. This is one instance of many within the history of optics where the desire for reward and its associated recognition among peers is no less strong within science as it is in other endeavours.

7.4.3 The Knowledge Framework

An examination of the range of ideas proposed at various times regarding the nature of light illustrates much about the way knowledge arises and develops. In Chapter 7 (section 7.5.2) there was a detailed description of four types of theories
which were extant during the later seventeenth and early eighteenth century, according to Cantor. That categorisation contrasts with the particle-wave dichotomy which is commonly described as the set of choices available. The way in which those viewpoints changed over the decades, the differences in finer detail which different scientists held for one or other theory and the refinements in each which were prompted by new properties of light or new objections (see Chapter 7, section 7.5.3) which were raised all illustrates how a knowledge system is constantly evolving. Which view becomes the more favoured one at any particular time is also influenced by more than rational argument – the reputation of those proposing one or other set of knowledge statements is often a significant determinant of the prevalence of one theory over any other. This was certainly the case with respect to the particle model which Newton, as its most prominent supporter, used and developed.

But even the seemingly successful viewpoints and knowledge statements do not necessarily last forever. Although the change in acceptance by everyone was by no means immediate, there was a later resurgence and eventual dominance of the wave theory resulting from the work of Young on interference, but more so by Fresnel in his description of a thorough mathematical wave-based description of all known properties of light in the first decades of the nineteenth century. The issues, including the socio-political ones, surrounding the developments at that time were discussed in chapter 7 (sections 7.5.2.4 and 7.5.8).

Knowledge is often constructed so as to explain the unfamiliar in terms of the familiar. The use of models and analogies is central to the explanation and development of theories and laws (see Chapter 7, section 7.5.5). This is clearly the case in attempts to describe light. Descartes used tennis balls and walking sticks in his descriptions, Newton imagined tiny particles (see Chapter 7, section 7.5.2.1) which exerted forces on each other as happens with ordinary objects (according to his then recently understood view of matter and gravity), Huygens pictured water waves which then were drawn as geometric diagrams in the style of Euclid and others considered light to be a fluid like water.

7.4.4 The Ethical Dimension

One aspect of an ethical dimension within science is illustrated with the personal motivation and rewards discussed above. On the one hand, those who work in science appreciate the reward which comes their way through recognition of their
work by others, especially when due credit is accorded them in the writings of another scientist. Equally, it is an accepted part of the professional ethos which exists within science that such recognition is forthcoming when warranted. It was in this area that Hooke found Newton wanting, as described in Chapter 7 (section 7.5.3). Such formalities were so much an accepted and expected part of the scientific enterprise that Hooke felt aggrieved that they were not followed in his case. Whether that deference was legitimately his due is another matter. It may well have been that his displeasure was caused by a lack of full understanding of the difference between his and Newton’s ideas.

7.5 Light and Colour

7.5.1 The Communication Dimension

Newton and Hooke provide detailed illustrations of the role of a communication system in science regarding developments in understanding how colours could be explained and how they could be accounted for in developing a model for light. In particular, they both were active contributors to the business of the Royal Society during the 1660s and 1670s. Their discussions and debates were referred to in Chapter 7 (section 7.4). All was not plain sailing in this regard however, with the younger Newton suggesting novel ideas which were at variance with Hooke’s ideas. The higher standing and longer experience which Hooke enjoyed in the Royal Society resulted in the review of Newton’s first communications regarding colour being undertaken by Hooke. Newton’s ideas were communicated by letter to the Society, but he also kept detailed private notes intended for later publication in some form. He also gave direct oral presentations to the Society, at least in the initial stages of his involvement with the group, but, because of what he considered annoying and incompetent objections from Hooke, he soon ceased communication with the Society and further public understanding of this aspect of optics was put on hold for some years as a result.

7.5.2 The Knowledge Framework

Descriptions of the properties of light involve not only its extrinsic behaviours such as refraction and interference, but also intrinsic characteristics such as colour. An examination of the way in which an understanding of colour has come about also provides an opportunity to study the Knowledge Framework in science. Newton’s
well known work involving prisms (see Chapter 7, section 7.5.10) enabled him to propose that prisms do not add or subtract anything from white light as was previously thought, but that white light was actually a combination of other colours. Descriptions of his work enable not only the deductive processes of scientific investigation to be studied, but also they provide opportunities to attempt replication of experiments and the problematic nature of that activity as outlined in Chapter 4 (section 4.10.4). Newton’s conclusions and resulting theory of light were derived from experimental observations and these, in turn, were a product of the technology sub-system of science. Newton required glass of good quality and this was shaped according to the various requirements specific to his needs. The Baconian experimental approach which focussed on systematic manipulation of the phenomenon being investigated meant that purpose-designed apparatus had to be produced. In this instance, it was the scientist himself (Newton) who constructed the apparatus (see Chapter 7, section 7.4).

7.5.3 The Aesthetic Dimension

The work of Newton, Goethe and others in relation to colour (see Chapter 7, section 7.5.10) also highlights an underlying desire to see beauty, harmony, simplicity, symmetry and inter-connectedness in natural phenomena and to use that as the driving force for observation and theory construction. This is seen clearly in discussions surrounding the nature of colour. Despite the current widespread acceptance of the seven-colour description of light, the process by which that number was determined, principally by Newton, was far from clear cut or objectively undertaken. Links to music and the desire to establish equal proportions among the colours have been considered the influential factors in Newton’s construction of a theory of colour, as was pointed out in Chapter 7 (section 7.5.10). Newton had considered other numbers of colours and, at one time, distinguished between main and boundary colours.

7.6 Interference and Diffraction in the Nineteenth Century

7.6.1 The Resource Dimension

At the individual level, monetary influences can be seen in evidence in optical developments during the 1810s. The prize offered by the Académie des Sciences for a successful theory to explain diffraction, while not necessarily the driving motivation
for Fresnel, was certainly the stimulus for bringing together, in the one document, his optical researches, which he undertook in collaboration with Arago (see Chapter 7, section 7.5.2.4). That ‘reward’ is often seen as a watershed in the debates between supporters of the emission and undulatory theories of light (the only two which remained by the 1820s as described in Chapter 7, section 7.5.8), although it was by no means the immediate end of the matter. Much later, Fresnel’s work was also formally recognised in England, by the Royal Society, with the awarding of the Rumford Medal in 1827. Others in the field (most notably Brewster as an emissionist) were also in receipt of similar Society awards which enhanced their standing and hence the arguments they put forward in favour of one or other view. The issue was still not completely resolved until the later 1840s (see Chapter 7, section 7.5.8).

The other aspect to the reward system, the less tangible one related to personal pride in being recognised for priority of discovery, can also be examined in the developments which took place during the first two decades of the nineteenth century. Young is still remembered for his experiment which demonstrated interference of light, although the pivotal status which is often accorded to that activity in current textbooks regarding the wave theory does not match the historical events as they unfolded. Certainly, it was not Young’s intention to develop a comprehensive wave theory for light based on the results of his interference experiments. In France, it was the work of Fresnel, supported by Arago, which lead to a complete theory of optics, but this was not without some vigorous and often heated debate between wave and particle theorists, particularly Arago and Biot. This is begins to indicate some overlap with the sociological aspects of the Organisational Dimension of science.

7.6.2 The Organisational Dimension

The rewards and prizes illustrate one way in which the scientists associated with optical developments in the early nineteenth century were formally recognised for their contributions and subsequently they experienced higher status within their field of research. The reputation which a scientist earned, either through tangible awards or as a result of peer acceptance of the quality of their work, was an important factor in the wider acceptance of arguments and ideas they proposed. Brougham’s reputation within the Royal Society and his belief in a particle model were significant influences in the lack of early acceptance of Young’s wave-related work. Arago actively aligned himself with Fresnel in furthering the wave model cause (particularly
to strengthen his attacks on the emission case put forward by his rival Biot. Brewster called on the reputation of his old colleague Brougham to support his final attempts to revive the particle model in the 1840s. These issues were described in Chapter 7 (sections 7.5.3).

7.6.3 The Communication Dimension

In the early 1800s, Young studied the phenomenon of interference and its significance in relation to his interest in the ether – some properties of light (for example, interference) could be used to illustrate the properties of the ether, just as could heat, electricity and other phenomena. As was pointed out in Chapter 7 (section 7.2), Young was not primarily attempting to develop a wave theory for light. His ideas were communicated to the wider scientific community via a series of lectures (which were also distributed in print) as well as papers published in the Royal Society journals and others. These lectures were more than another step in the development of optical theories. They also highlighted the sometimes controversial nature of a scientist’s work and the way it is communicated to others. Young’s lectures were not generally well-received, and this has been attributed variously to poor communication skills, to the lack of quantitative rigour employed by Young and to a lack of detail in his explanation of how he performed his experiments (see Chapter 7, section 7.5.2.2). Nevertheless, it is the content of that series of lectures which are nowadays often quoted as being the turning point for the eventual success of the wave theory of light, even if they were not seen as such at the time.

The communication dimension was not always an automatic source of knowledge dissemination and stimulus for further research however. Partly because of the mixed success which Young experienced in his various communications and partly because of the strength of Newton’s emission theory, the latter was still the dominant belief for a further decade or more. Certainly this was the case in France where the particle theory had gained further status with the application of a mathematical analysis based on the work of Laplace. There was little chance of a wave theory gaining any further understanding, not to mention acceptance, in that country due to the work of Young because his ideas had not reached there until after 1815. There appeared to be a deliberate attempt on the part of particle theorists in Europe to suppress any works which provided support for a wave theory (see Chapter 7, section 7.5.3). The Organisational Dimension within science was seen, in this
instance, to exert sufficient influence over the communication system to limit what might otherwise have been a natural progression and development of scientific knowledge. In other words, the dimensions within the scientific enterprise cannot necessarily be examined independently of each other.

7.7 The Speed of Light

7.7.1 The Organisational Dimension

The speed of light had long been a topic of debate when Descartes indicated that his whole philosophy relied on his assertion that it was instantaneous. As a consequence of his reputation, this was the belief held widely during the seventeenth century. Evidence to indicate that light travelled at some finite speed first became available as a result of studies of the planets made possible after the development of the telescope, as has been described in Chapter 7 (section 7.5.6). In particular, fluctuations in the observed times for the rotation of the moons of Jupiter prompted Roemer to suggest that the time taken for light to cross the earth’s solar orbit was a possible cause. He put forward the idea while he was working as an assistant to Picard at the French observatory (the latter being replaced in the mid 1770s by Cassini). Despite Roemer’s presentation of his suggestion to the Académie des Sciences general acceptance was not forthcoming, due in part, perhaps, to his youth and lack of general recognition and also to the weight of opinion proffered by Cassini whose reputation was widely known. The strength of Cassini’s position is even further indicated by the support which Roemer’s idea gained from Huygens in 1679 and which was still insufficient to sway Cassini and hence the majority of the scientific establishment at the time.

7.7.2 Underlying Beliefs

Descartes’ assertion (see above) that light was an instantaneous phenomenon was a view he held only partly on the basis of physical evidence. His position on this matter arose initially as a belief, which he later justified by reference to lunar shadows and the like.

A central belief in relation to the propagation of light, irrespective of its speed, was the notion that light had to have something to move through. Its motion was described in terms of how it moved through an ‘ether’, and how the constitution of the ether affected its motion. For some, light was actually described in terms of
motions within the ether. Properties of the ether such as its elasticity and density were inferred from estimates of the speed of light through it (Chapter 7, section 7.5.6). There had never been any evidence to support the existence of an ether. Its presence was taken as a philosophical given by many, from Aristotle to Descartes, on the basis that nothingness cannot exist when surrounded by matter – the matter would instantly rush in to fill the void. The importance of this belief was described more fully in Chapter 7 (section 7.3.2).

7.7.3 External Connections

Strong connections can be seen between discussions of the speed of light and astronomy. Although astronomy is a scientific pursuit, it is nevertheless significantly independent from optics to consider it ‘external’ to the primary area of science under study, and to examine the influences which two areas might have on each other’s development. As indicated above, the possibility that light had a finite speed was first mooted as a result of astronomical studies – the proposal of Roemer. Further astronomical investigations to determine the size of the earth’s orbit around the sun enabled a quantitative determination of the speed of light (see Chapter 7, section 7.5.6). Developments in relation to light’s speed were dependent on progress in a different area – astronomy.

This dependence has not all been one way, however. Once the existence of light’s speed had become accepted after the work of Bradley in the 1720s, it was possible for astronomers to make more confident predictions of the timings of various phenomena during the course of a year. Previously there had been an awareness of a variation in time of cyclical phenomena, but accuracy of measurements or artefacts of the process of measurement could not be ruled out as sources of the variations until the effect of the speed of light across the earth’s orbit was understood. There was, then, a mutual dependence of progress in one area upon developments in discipline of science.

7.8 Conclusion

Chapter 7 examined many of the developments which took place in optics during the period of time from 1600 to about 1850. The current chapter illustrated how aspects of that history could be overlaid on the curriculum design framework
developed in this research as a plan for a teaching unit. This examination has demonstrated the main points of this thesis:

♦ there is more which can and should be studied in science than just the knowledge content of current secondary school science courses,

♦ an examination of these other characteristics of science provides a clearer view of the culture and processes of science,

♦ this broader analysis requires a study of the history of science, and

♦ a curriculum design framework derived from the cultural analysis advocated by Lawton and applied to a topic currently taught in senior secondary school physics courses provides the means whereby the current conceptual content can be retained while educating for the broader view of science as has been argued for in this thesis,

♦ it has been shown to be possible to design a curriculum which addresses issues of scientific literacy and the nature of science by teaching physics through a historical approach.

A study of some era or discipline in science at the secondary school level using an historical approach requires students to have an analytical framework which is predetermined. Without that, students would be studying the history in a different way – they would be studying the history with a view to producing their own analysis of science. This, in effect, would be a History of Science course \textit{per se}, as distinct from a science course with an historical approach. While there may well be some merit in students undertaking such a course, the focus of this research is on changing the approach to current science courses rather than arguing for the introduction of a completely new subject. Consequently, students should be given a set of characteristics of science – the Dimensions of Science - which they can use as a basis for their study of science through history.

The framework proposed in this thesis has been one derived from Lawton’s curriculum development approach. His model was the product of his cultural analysis approach to education in general, that is, his starting point was that education is concerned with the transmission of the most valuable aspects of the culture of a society. This thesis has applied that approach to the society of science and its culture. The result has been the list of “Dimensions of Science” (which Lawton referred to as
‘cultural invariants’) which appear in the right-hand column of Figure 8-1. These invariants should be seen in any episode of scientific activity, irrespective of the era or content, if one examines the activity in sufficient detail. The discussion of this chapter, centring on Figure 8-1, has shown how all of the ‘invariants’ can be illustrated while studying the range of concepts which are commonly used to define a course in optics at the secondary school level. The specific historical aspects referred to in the discussion of this chapter are not intended to be definitive in that it is not proposed that they are the historical episodes and analyses which must be incorporated in an optics course which was taught from an historical base. The intent of this chapter is to show that each of the dimensions of science is able to be illustrated during a study of developments in optics. It is equally possible that they could have been illustrated by reference to other episodes. For example, the Communication Dimension in science was highlighted in discussions related to Microscopes and Telescopes, Refraction, Light and Colour, and nineteenth century Particles and Waves debates. That dimension could equally well have been highlighted during a historical discussion of events and debates surrounding the Speed of Light. Indeed, all of the characteristics and dimensions of science could have been drawn out of a sufficiently detailed study of developments in relation to the speed of light. However in order to achieve the latter, a depth of study may be required which might be inappropriate for a secondary science course.

The essential point shown in this thesis, and particularly in the current chapter, is this. The characteristics of science can be illustrated within a study of optics by the appropriate application of the curriculum design framework proposed in Chapter 6. The same could be achieved for any topic within a science course if an appropriate study of historical developments is undertaken. Once such a curriculum outline is drawn up, the next step, according to Lawton, is to Design the Teaching and Learning Program, incorporating this cultural analysis of science, as described by Step VI in Figure 6-6 in Chapter 6. That process, and the subsequent Steps described therein, are beyond the scope and intent of this thesis.
CHAPTER
8

CONCLUSION

8.1 Overview

This research set out to investigate the incorporation of a study of the history of science in the science curriculum at secondary education level. The initial rationale for such an approach was twofold. Firstly, the history of science is an inherently interesting focus of study for students, and, secondly, it is fundamental to gaining an appreciation of the nature of science. It was not the intention to create a entirely new subject for secondary education, however. Apart from the difficulties associated with the introduction of new subjects in an already crowded curriculum, it was seen to be important to develop a different approach to the current curriculum which all students study. An appreciation of the history of science should not be seen as an additional area of study, but should provide the framework within which compulsory science education is developed. Science education curricula need to change so that the current images of science which students form, these images created mostly through subliminal messages not only from teachers but also from the popular media in various program formats, are redrawn to produce a clearer understanding of what science is and how the scientific enterprise is enacted. Even where there is no conscious attempt by the teacher or the curriculum designers to convey ideas about what science is and how scientists carry out their work, students still construct their own mental images of what science involves. Invariably, these do not correspond with the picture most observers would describe.

8.2 Research Questions Revisited

Question 1

The preliminary question which was examined in relation to this history of science research was described in Chapter 1 (section 1.2) was as follows:

To what extent has there been on-going academic discussion which recognises the value of the history of science in secondary school science education and what are the implications of this discussion for curriculum development?
A study of the literature related to the use of history of science in science courses was described in Chapter 2, and revealed that there have been wide-ranging contributions over time regarding the general concept of incorporating the history of science in secondary education, including the central importance of that history in the achievement of scientific literacy. However a gap appeared in the spectrum of ideas which had been debated. There were significant arguments put forward to espouse the worth of using history in science, there were various viewpoints expressed surrounding the concepts of scientific literacy and there were numerous illustrations offered to describe actual courses taught. But the ‘middle ground’ was sparse. If the general principle of a historical approach is accepted, and if there is broad agreement on the scientific literacy goal, then there needs to be a curriculum design framework produced to enable a teaching program to be properly constructed. It is this area which appears lacking in all the discussions on history in science in secondary science education. This research was undertaken to fill that gap.

**Question 2**

*What does the current focus on science literacy imply for the design of a secondary school science education curriculum?*

The concept of scientific literacy has gradually evolved since the term was first used during the 1950s, and this evolution was described in Chapter 3, along with the characteristics of related themes such as “Science For All” and “The Public Understanding of Science”.

As indicated above, a central function in examining the history of development of ideas in science is the opportunity it provides to analyse the characteristics of science which incorporate what is commonly referred to as ‘the nature of science’. In Chapter 4 there was an examination of a range of features and characteristics of science discussed, based on the importance of developing a view of science which was different from the more widely held, but narrowly focused, perception of the purposes, processes and products of science.

The ideas developed in Chapter 5 demonstrated a fundamental and essential connection between the history and nature of science and the attainment of scientific literacy. In addition to any pedagogical value in the incorporation of history in science education, the argument was put that the goal of scientific literacy is only
achievable if those associated with producing or implementing science curricula adopt a historical approach to course design and development.

**Question 3**

*If there is a clear connection between scientific literacy, the nature of science and the history of science, how should a science curriculum be designed so as to firmly establish and demonstrate the links between these concepts?*

There has been much effort devoted to individually tailored courses which have employed history in some way in science education and some of these were referred to in Chapter 2. While the central *theme* of this research initially concerned history in science, the central *solution* has been the production of a curriculum design framework which, it has been argued, should underpin the development and implementation of a specific curriculum outline in any area of science education. This work was influenced by the general curriculum design concepts of Lawton; these were modified and adapted in this research to enable them to clarify an approach to curriculum design in science, while still retaining the essential features of Lawton’s approach. Nine Dimensions of Science were proposed. Initially, during the early drafting stages of the thesis, a direct alignment was sought to link the characteristics of science discussed in the Nature of Science chapter under one or other of Lawton’s nine Systems of Society. These attempts proved to be somewhat strained and the links with science were tenuous at times and so it became apparent that key themes other than Lawton’s nine would be required if the enterprise of science was to be depicted as a community or ‘society’ in its own right. An initial list of some fifteen or more themes seemed somewhat lengthy and too specific, so it was reorganized into what became a nine item list, without deliberately attempting to match Lawton’s number – he was not insisting on nine as being a definitive number in any case. Interestingly, these final themes (referred to as the Dimensions of Science) turned out to be similar to those on Lawton’s list. The examination of the characteristics of science, independent of Lawton’s cultural analysis, eventually produced a set of dimensions which bore a clear similarity to his more general cultural characteristics.

As has been emphasised elsewhere in this research, the purpose has not been to produce a definitive analysis of the history of science, nor of the sociology of science or the nature of science. The primary intention is to propose a workable
framework on which to base the design of a science education program using a historical approach. The Dimensions of Science provide a framework for that process. It would not be contrary to the spirit of this thesis if additional dimensions were added or if was deemed suitable for some to be amalgamated. Lawton was flexible in that regard also. The essential point is that the Dimensions of Science framework (or one of similar composition) should be employed to design a science curriculum.

**Question 4**

_Could the broad framework of such a curriculum design provide an effective basis on which to develop a teaching program in a specific area of science?_

Having a framework on which to base the development of a curriculum is a fundamental starting point. The framework was proposed in Chapter 6 and its effectiveness in implementation was demonstrated in a specific curriculum situation in Chapter 8. A common senior physics topic area is that of Optics. Chapter 8 illustrated how the framework could be applied, with some degree of flexibility, to produce a curriculum which addresses the science literacy goal. To develop a curriculum based on the history of science it is naturally necessary to be aware of that history. Accordingly, prior to the curriculum development exemplar in Chapter 8, there was a detailed study of the history of optics focusing on aspects which could be employed to illustrate each of the Dimensions of Science in the development of a teaching program.

**Question 5**

_What changes would need to occur to enable such a curriculum design approach to be implemented?_

Having established the importance and practical feasibility of a curriculum design framework which incorporates the history of science and addresses the scientific literacy imperative, the next step is to consider its implementation. Whilst this question was not intended to be examined formally within this research, it is implicitly addressed in part through the discussion of the history of optics in Chapter 7. If a historical approach is to be adopted for science education, then it is clear that teachers need to have some appreciation of that science and this requires a study of its history.
This points to one important change required if new curriculum directions are to be adopted: teacher education needs to bring potential and existing teachers in contact with the history of science. Such studies and an understanding of how they are central to an education about science need to be incorporated into teacher training programs at tertiary institutions. It has been widely reported that the teaching of science at secondary level continues to follow the traditional disciplines within science, even in the lower secondary years, despite any encouragement there may be even in state and national curriculum guidelines to do otherwise (Goodrum, Hackling and Rennie, 2001). For the vast majority of science teachers, the only experience they have of science is their own tertiary level studies undertaken prior to teacher training. Inevitably, their teaching content and style reflect that background unless they have been exposed to viewpoint which challenge that approach. Hence any new curriculum design initiative needs to address those teacher shortcomings if new approaches are to be adopted successfully. Pre-service teachers should have an appreciation of the character of science if they are to understand the significance of its products. In addition to pre-service training, there would naturally be a need for in-service training to be made available for those teachers who are already in the classroom. This additional training would need to be on-going rather than short term, as fundamental changes in approach to science teaching philosophy would be required.

The second area of change would be to the description of science courses. While there has been some change in this regard in many of the new curriculum statements in many countries, the extent of the change beyond broad suggestions for new directions in science education has been limited in most Australian states at least. As long as course outlines appear to bear close connections to the traditional science disciplines, teachers are likely to retain the approaches referred to by Goodrum, Hackling and Rennie (2001). Such documents need to clearly reflect new directions and changed emphases, and thereby to provide encouragement for teachers to adopt different approaches.

The third requirement for implementation is the more ready availability of resources. Initially it is the teachers who will need easy access to material which enables them to develop a broad background in both general issues associated with the nature of science as outlined in Chapter 4, and in specific developments in a range of areas of the history of science such as the history of optics examined in Chapter 7.
Subsequent to this teacher familiarization, there will be a need for resources which are appropriate to classroom use.

The fourth area of change required to enable a historical approach to be implemented is in some ways the most crucial. For a variety of reasons, what a teacher teaches and how it is taught is strongly influenced by the nature of the assessment tasks which students must undertake in year levels where such tasks are externally imposed and graded. Consequently, if there is no change to the form and focus of assessment, there is little chance that teachers will adopt and maintain new curriculum approaches even if their worth is demonstrated in pre-service and in-service training courses.

8.3 The Central Question Answered

*Can the history of science be employed as an effective approach in the teaching of science at secondary school?*

This research has shown that a curriculum can indeed be designed on a framework which is based on an understanding of the history of science. However the arguments and illustrations supporting the case for history went beyond demonstrating feasibility, which was the initial aim of the research. If the scientific literacy imperative is to be adopted, then the history of science becomes an essential vehicle for the development of an understanding of the nature of science and the many inter-relationships which exist between science and society.

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