Chapter 7
Conclusion: Understanding the Elusive Nature of Objectivity

An evaluation of research in science education reported in this book shows the problematic nature of understanding some of the universal values associated with objectivity such as certainty, value neutral observations, facts, infallibility, scientific method, and truth of scientific theories and laws. Similarly, aspects of Merton's "ethos of science" such as open-mindedness, universalist, disinterested, and communal have also been invoked to understand progress in science. Studies evaluated, however, have pointed out that some of these values are not necessarily essential for understanding objectivity. Philosophy of science itself has explored new territory in this context and Giere (2006a, p. 95) considers that it is *presentist hubris* to think that we can have an objectively correct or true theories. Daston and Galison (2007) have constructed the evolving nature of scientific judgment (objectivity) through the following phases: truth-to-nature, mechanical objectivity, structural objectivity, and finally trained judgment. Each of these regimes did not supplant the other but they can coexist and supplement each other at the same time. Although objectivity is not synonymous with truth or certainty, it has eclipsed other epistemic virtues and to be objective is often used as a synonym for scientific in both science and science education.

Table 7.1 provides an overview of the classification of all the articles evaluated in this book. Following are some of the salient features of the results obtained: (a) S&E was the only journal in which two articles were classified in Level V, which approximates to the evolving nature of objectivity; (b) In all the chapters most of the articles were classified in Levels II and III; (c) Classification of the articles in Level III (62% for JRST, and 44% for S&E) means that the authors recognized the problematic nature of objectivity and hence the need for alternatives; and (d) Very few articles were classified in Level I (none for HPST and ESE), which approximates to the traditional concept of objectivity as found in most science textbooks. These results provide a detailed account (over a period of almost 25 years) of how the science education research community conceptualizes the difficulties involved in accepting objectivity as an unquestioned epistemic virtue of the

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Table 7.1 Comparison of the levels of classification of articles in different chapters of this book

		No. of articles classified in level				
Chapter (Journal)	*n*	I	II	III	IV	V
3 (S&E)	131	5	56	58	10	2
4 (JRST)	110	4	33	68	5	–
5 (HPST)	8	–	4	3	1	–
5 (ESE)	12	–	6	4	2	–

Notes:
1. For a description of levels I–V see Chap. 3
2. *n*: Total number of articles evaluated
3. S&E: *Science & Education*
4. JRST: *Journal of Research in Science Teaching*
5. HPST: *International Handbook of Research in History, Philosophy & Science Teaching*
6. ESE: *Encyclopedia of Science Education*

scientific enterprise. Nevertheless, it seems that more work needs to be done in order to facilitate a transition (Levels IV and V) toward a more nuanced understanding of objectivity and eventually the dynamics of scientific progress.

Following are some aspects for facilitating an understanding of the elusive nature of objectivity based on articles evaluated in S&E, JRST, HPST, and ESE. Furthermore, based on the evaluation of general chemistry textbooks the idea of "transgression of objectivity" is introduced. It is plausible to suggest that these findings have implications for science education which are synthesized and discussed in the following sections (Based on Chaps. 3, 4, 5, and 6 and presented in alphabetical order):

7.1 Alternative Interpretations of Data in Science and Objectivity

Science textbooks generally expound on a series of theories that deal with a topic and it is tacitly understood that theoretical and methodological standards for selecting a theory are neutral and objective. However, what is missing is an essential aspect of scientific progress namely based on alternative theoretical frameworks the same data can be interpreted differently by scientists before reaching consensus with respect to the canonical nature of science. Reproducibility of scientific experiments is generally considered to contribute to the objectivity of scientific knowledge. However, this ignores the difficulties faced by students and even scientists to reproduce and interpret experimental results. Thus, the subjectivity involved in different interpretations is necessary for understanding the dynamics of "science in the making." Alternative interpretations of data provide students the opportunity to understand that progress in science involves rivalries and uncertainty, which precisely leads to controversies among scientists.

7.2 Alternative Research Methodologies and Objectivity

Scientists in different disciplines have distinct epistemic goals and practices and consequently their conceptions of rationality and objectivity can also vary. However, science is generally portrayed as a source of objective knowledge and a possible contribution of scientific narratives based on students' thinking is considered to be subjective and thus ignored. An example of alternative research methodologies is the mixed methods research based on interviews (among other methodologies) with the students that can facilitate more positive attitudes toward science. In a sense this corroborates what scientists themselves do by interacting within the scientific community (i.e., trained judgment as suggested by Daston and Galison, 2007). It is plausible to suggest that the objectivity of science (and also mathematics) rests on the criticizability of the different arguments put forward by the scientists.

7.3 Canonizing Objectivity to Reinforce Privileges

Academic achievement gap between different sectors of a society is a cause for concern (e.g., African American and white students in the USA). Dominant groups in a culture generally support the existing structure of objective knowledge and any attempt to question it is considered as opposition and insubordination. This leads the dominant group to consider its understanding as the canonized version of objectivity. Similarly, science also provided the objective evidence of the natural inferiority of women, the homosexuals, the colonized, and the enslaved. Furthermore, science is often envisioned as directly reflecting the truths in science and therefore unquestionable. Diversity of views helps to understand objectivity and it is undermined if the objective correctness of a claim is taken to be what is endorsed by a privileged point of view.

7.4 Empiricist Epistemology and Objectivity

School science generally emphasizes an empiricist epistemology in which a "purified" version of science is considered essential for achieving the "unobtainable" ideals of truth and objectivity. In the late nineteenth century the manipulation of physical objects and instruments helped to reframe mathematics and astronomy as a physical science, which facilitated a culture of objectivity. Such practice leads to a "myth of experimenticism" namely following the path from experiment to theory (emphasis on empirical methods) not only does not provide greater objectivity but also deprives students of an environment that facilitates thinking and understanding arguments. Contrary to popular belief in science education, simple Baconian stockpiling and ordering of observations does not facilitate the formation of better scientists.

7.5 Femininity-Masculinity, Science and Objectivity

According to feminist critics (Harding, Keller, and Longino) science has grown out of a Western male tradition that celebrates objectivity and power relations based on masculinity that leads to dualisms such as: rational-emotional, logical-intuitive, objective-subjective, and abstracted-holistic. Both science and science education assert the relationship between masculinity and traits such as objectivity, rationality, and lack of emotion. Furthermore, if femininity is viewed as mutually exclusive with masculinity, this also leads to femininity being considered as lacking the scientific traits. The politically engaged standpoint of feminism is less partial and distorted than the standpoint of conventional scientific inquiry. Overcoming such simplistic relationships and dualisms can facilitate a critical examination of science and a better understanding of gender in science education. This conflict between masculine and feminist traits can at times lead women to abandon careers in science. Similarly, the abstraction and objectivity of pure science have masculine connotations, whereas the human and social sciences are considered to be feminine.

7.6 Interaction Between Evidence and Belief (Faith) and the Quest for Objectivity

Interactions between evidence and faith become important in controversial issues such as teaching evolution in a biology course. The dilemma faced by the teacher is based on the fact that although students may seem to understand evolution (based on evidence) they generally do not believe in it. In such cases, the cultural milieu of the students in which the subject is taught is important. It is even suggested that today's teacher of evolution faces a situation very similar to Darwin when he presented the *Origin of Species*. Consequently, the interaction between the understanding based on belief in the absence of objective evidence and acceptance based on evidence can provide a better understanding of the nature of science. In general, teachers' perceptions and beliefs about learning also affect how they approach the material and what they teach. At this stage a word of caution is necessary: if our goal as teachers is to get students to believe the content we teach—then that may be considered as indoctrination and not education (I owe this observation to Aikenhead, 2016). More recently, based on contemporary epistemology/philosophy of mind scholarship, Smith and Siegel (2016) have clarified that belief is involuntary and need not be used as a basis for inference or action, whereas acceptance is voluntary and involves a commitment to use what is accepted in one's practical reasoning.

However, it is important to note a caveat based on history of science, which shows that in some cases even scientists do not agree with respect to the interpretation of evidence as they have different prior epistemological beliefs. In other words, changes in science can occur by means other than rational consideration of empirical evidence. Furthermore, although objectivity is a value that all scientists strive for in their work, what is a fact in science is continually reevaluated in the light of ongoing research.

7.7 Mertonian "Ethos of Science" and Objectivity

Merton's (1942) "ethos of science" is based on norms of universalism, communism, disinterestedness, and organized skepticism. Merton believed that these institutional values are transmitted by precept and example, perhaps during the course of a scientist's educational career and can even be considered as the idealized "view from nowhere" (Reiss, 2014). Is there a contradiction between Merton's "ethos of science" and Daston and Galison's understanding of objectivity in science? It seems that increasing commodification may jeopardize Mertonian norms of openness in scientific practice, truthfulness, objectivity, trust, accuracy, and respect for expertise (Vermeir, 2013). Similarly, social constructivism may jeopardize Merton's "ethos of science" (Slezak, 1994). Longino (1990) underscores the need for criticism from alternative perspectives and thus postulates a social structure for achieving Merton's "organized criticism." Merton's universalism does seem to imply the objectivity of scientific knowledge (McCarthy, 2014). However, if we do not conflate objectivity with universal and unconditional correctness of scientific knowledge, but rather consider scientific inquiry to provide a greater degree of objectivity (Daston & Galison, 2007), then Merton's ethos of science can still provide guidance. Despite these difficulties, it seems that Mertonian norms of the scientific enterprise can be reinforced by following the process of trained judgment rather than mechanical objectivity.

7.8 Objectivity as a Process and not a State

Understanding of constructivism in Piaget's theory of cognitive development and genetic epistemology has been the subject of considerable controversy in science education research. In this theoretical framework, construction of knowledge by the child is the result of a subjective knower within a social context that facilitates transformation, organization, and interpretation of structures leading to a dialectical interaction. An important implication for science education is that "objectivity is a process and not a state" (Piaget, 1971) that means a continuous series of successive approximations toward objectivity that may never be achieved. In other words, objectivity is not an "all or nothing thing," but rather it comes in degrees (Machamer & Wolters, 2004). Similarly, in Piaget's genetic epistemology, studying the psychological subject can lead to an approximation toward the epistemic subject. This means that a classroom teacher needs to be more concerned about the process (and not the product) that can facilitate an approximation toward what may be considered as objective or even perhaps iconic knowledge in a particular domain of science content. Research reported in science education provides evidence for constructivist teaching strategies that facilitate change by taking into consideration students' alternative conceptions as part of the process of conceptual understanding. Such experiences lead to innovative teaching strategies based on the following: audit the process rather than the product. Similarly, Gergen's (1994) understanding of objectivity as involving the dynamics of process-product complements Daston and Galison's (1992) truth-to-nature. It is plausible to suggest that the underlying ideas of Daston and Galison, Gergen and Piaget (formulated in different domains of knowledge) go beyond the positivist understanding of objectivity and even complement each other. Similarly, it seems that there is a possible relationship between Cushing's (1995) idea of *contingency* and the historical evolution of the regime of objectivity as presented by Daston and Galison (2007). Cushing refers to the hegemony of the Copenhagen interpretation of quantum mechanics over its rivals on non-epistemic reasons, that is on grounds that were not necessarily objective or rational. In Daston and Galison's (2007) framework this could be understood as an episode in which trained judgment of the community prevailed. It is plausible to suggest that it is perhaps the contingent nature of science (Cushing, 1995) that manifests itself in the evolving nature of objectivity. Quantum mechanics and valence theory provide good examples of such changing or competing theories (cf. Niaz, 2016).

7.9 Objectivity and Value Neutrality in Science

As scientists are part of a society, the notion that a scientific expert can be entirely neutral, value-free, and objective is difficult to understand. Despite efforts to present science as objective and autonomous, its relationship with capital and market forces is well known, and at times a picture of value-free science is presented as more of a romantic principle. The argument for a value-free science is difficult to sustain as most human activities are value-laden and historians of science have recognized this facet of the progress in science. Consequently, although historians, philosophers of science, and science educators may aspire for a science that is value-free, neutral and objective, the real picture of the scientific enterprise is much more complex. Furthermore, insisting on the objectivity and neutrality of science and ignoring the social forces that determine its progress does not facilitate a critical appreciation by students. Following are some examples of topics that involve ethics and values: depletion of ozone layer, genetics, gene therapy, stem cell research, xenotransplantation, napalm, agent orange, pollution, nuclear weapons, garbage collection, among others. Furthermore, history of science shows that facts have rarely been loyal to values which initially led to their identification. A good example is Darwin's use of facts that had been gathered by his teleologically oriented predecessors associated with a different set of values. In the case of gender and phrenology, objectivity and neutrality of the scientific enterprise was compromised. Consideration of the problematic nature of value neutrality leads to a thought-provoking question: if the ideal of value-free inquiry is flawed, what is to replace it? Based on Longino (2002), a possible alternative is "social value management" which involves non-epistemic values (social, economic, and other) (Irzik, 2015). As science is a human construction, scientists first prefer their own interpretation of the data, which may or may not change (or change partially) under the scrutinizing lenses of the scientific community. In this context, it would be interesting if courage, humility, and willingness to suspend judgment can also be considered as necessary values in the scientific enterprise. Holton (1978a, b) has, for example, recognized the role of "willingness to suspend judgement" in the historical reconstruction of the oil drop experiment. It is plausible to suggest that there is an underlying tension between scientific progress and the assumptions with respect to its neutrality and objectivity.

7.10 Objectivity-Subjectivity as the Two Poles of a Continuum

In most educational systems, the virtues of the traditional scientific tradition (rationality, objectivity, and skepticism) are challenged by strands of irrationality, subjectivity, and credulity and this can pose considerable problems for the science teacher. However, such dual ways of thinking also formed part of the progress of science itself. Precisely, the evolving nature of objectivity based on the history of science can be a source of guidance for the educational community.

Quantitative research methodology in education can be associated with positivistic styles of thinking. On the other hand, integration of qualitative and quantitative research methodologies can provide a better understanding of objectivity by facilitating competition between divergent approaches to research. In the interpretive research paradigm (social constructivist), traditional standards of internal and external validity, reliability and objectivity are replaced or complemented with notions of credibility, transferability, dependability, and confirmability. Triangulation based on different data sources is particularly helpful in enhancing credibility of the research. Such research experiences inevitably recognize the relationship between objectivity and the underlying subjectivity that leads to the creation of multiple realities. The dualism between objectivity and subjectivity leads to a conflict in the evolving nature of progress in science. Ignoring this duality may lead to the hegemony of objective knowledge and the consequent emphasis on rote learning. During scientific research, subjective and objective aspects interact by means of communication and peer reviews within the scientific community. In the case of students' thinking of nature of science, it is plausible to suggest that it progresses from one pole of empiricist epistemology to another, which considers subjective limitations in both components of scientific knowledge, namely empirical evidence and coordinating theory. It has also been argued that in qualitative research a detached observer claiming objectivity would not be able to access suitable data. Daston and Galison (1992, p. 82) have referred to a similar tension between subjectivity and objectivity, in the history of science itself. In other words, the personal construction of the students (subjective) can always be contrasted with the objective canonical knowledge, leading to integration. Those who work in the lab (both students and scientists) can face a dilemma when they have to deal with the subjectivist doubts with respect to observations. It is plausible to suggest that "trained judgment" could be one alternative to reach consensus with respect to the interpretation of observed data.

At present there is considerable debate in science education with respect to assessment of students' performance based on multiple-choice questions (considered objective) and conceptual problems (considered subjective). Despite this debate, the research community also recognizes that multiple-choice questions are generally based on memorized algorithms and do not facilitate meaningful learning of science content. The tension between subjectivity and objectivity in assessment provides an opportunity to reflect upon the very essence of the scientific enterprise, namely doing and understanding science involves interpretation and not just memorizing algorithms, hence the importance of conceptual problems. Furthermore, school science is generally considered to be *scientific* that is characterized by rationality, precision, formality, detachment, and objectivity. In contrast, *everyday* science is considered to denote an opposing set of characteristics such as improvisation, ambiguity, informality, engagement, and subjectivity. It can be argued that the two sets of characteristics are not dichotomous but change continuously depending on the needs of the school environment.

In controversial topics of the science curriculum such as evolution, the instructor with a professional training in evolutionary biology thinks that he is being objective, and still at the same time in his interactions with the students he/she is forced to grapple with issues that require subjective understanding. This once again illustrates the subjectivity–objectivity interface in the context of teaching science. Similarly, other topics of the science curriculum can also face similar dualities that are subject to refinement.

7.11 Open-Mindedness and not Relativity Helps in Understanding Objectivity

Objectivity and open-mindedness are indeed integral attributes of the scientific enterprise, but not in the sense generally presented in school science and textbooks. Objectivity consists not in denying preconceptions/presuppositions, but in the ability to modify beliefs in the light of emerging evidence and also encouraging open-mindedness. Scientists make errors and it is the community of scientists that helps to facilitate change by espousing open-mindedness. History of science shows that although scientists at a certain stage may have good reasons to believe that they need to go beyond objectivity, this does not represent relativity but rather open-mindedness. This serves to enhance the objectivity of collectively scrutinized scientific knowledge through decreasing the impact of individual scientists' idiosyncrasies and subjectivities. For example, although some creationists reject objectivity and relativize the truth of scientific knowledge, they are not necessarily open-minded. Another example of this aspect is the initial acceptance of the paramyxovirus as the causative agent of SARS and its replacement by the coronavirus, which illustrates not only the tentativeness of science but also skepticism and open-mindedness (Wong, Kwan, Hodson, & Jung, 2009). In the classroom, inclusion of such episodes from the history of science can facilitate a more meaningful pursuit of scientific inquiry.

7.12 Polanyi's Tacit Knowledge and Objectivity

According to Polanyi (1964, 1966), the rule bound knowing of empiricism and logic is linked to objectivity and the tacit knowing based on intuition and passion is linked to subjectivity. Consequently, personal knowledge is the unification of the objective and subjective aspects of scientific knowledge. In a similar vein, Daston and Galison (2007, p. 377) have endorsed Polanyi, by suggesting that logical positivism approximates to mechanical objectivity, whereas what scientists actually do (based on tacit knowledge) represents trained judgment. According to Guba and Lincoln (1989), tacit knowledge is all that we know minus all we can say, consequently, "… if the investigator is to be prohibited from using tacit knowledge (Polanyi, 1966) as he or she attempts to pry open this oyster of unknowns, the possibility of constructivist inquiry would be severely constrained, if not eliminated altogether" (p. 176). It is precisely the "tacit assumptions" that underlie the frameworks scientists use to design and develop their research programs that lead them to emphasize reason, empirical evidence, and objectivity. Furthermore, it seems that scientists are probably less reflective of "tacit assumptions" that guide their reasoning than most other intellectuals of the modern age (Blake, 1994). This shows that science education needs to recognize both mechanical objectivity and trained judgement and thus recognize the problematic nature of objectivity.

7.13 Positivism and Its Claims to Objectivity

School science generally promotes the idea that experiments provide data that reflected what was actually happening in the real world. Emphasizing such universal knowledge in the classroom based on a positivist perspective ignores the role of conflicting paradigms (controversies) and thus does not facilitate an understanding of how science progresses. Objectivist teaching strategies are heavily imbued with positivist epistemology that relies on algorithmic rather than conceptual understanding. In contrast, postpositivist perspectives in the philosophy of science (Phillips & Burbules, 2000) provide a better understanding by facilitating an integration of domain-specific information (plausibility of hypotheses) and domain-general aspects of the nature of science (heuristics that guide explorations). One possible sequence of a conceptual teaching strategy could be: setting up of a sequence, opening question, dialogue, conflicts (based on controversies), and negotiation of meaning. Objectivity, certainty, and infallibility as universal values of science may be challenged while studying controversies in their original historical context.

7.14 Reporting Style in Science as a False Guise of Objectivity

How we communicate science is an essential part of understanding "science in the making." Science and science education generally emphasize that researchers should maintain an objective voice (i.e., passive), and not to be passionately involved with their findings and interpretations. However, history of science shows that this is at best a chimera (Daston & Galison, 2007; Duhem, 1914; Hoffmann, 2012, 2014; Medawar, 1967), and research that matters is motivated by deep commitments and the passion to learn and understand. Indeed, reporting science involves a constant struggle between the theoretical frameworks of the scientist and the historian, as both are theory-laden. Given the influence exerted by editors and even the scientific community, scientists face a conflict with respect to using passive or active voice while reporting their findings. The active voice potentially recognizes the human dimension in data interpretation and knowledge construction. Given the complexity of the scientific enterprise, laboratory methods of gathering data and their interpretation may change over time due to some unforeseen findings. Still reporting of such research, written in retrospect is presented as highly consistent, rational, and logical from its inception. Consequently, reporting of a scientific event in a journal entails covering up the confusion, random, and chaotic means that produced it so as to give the impression that it represents an objective reflection of the world as it really exists. For science education the inclusion of the human element in the form of historical narratives is particularly helpful.

7.15 Role of Affect/Emotions and Objectivity

Studies of affect in science education are theoretically wide ranging and empirically diverse. In science education, emotions have generally been opposed by reason, truth, and the pursuit of objective knowledge. It is recommended that teachers (for that matter also students) should not express emotions as they are biased and thus there is no place for them in teaching and learning science. However, the difficulties involved in educational practice lead to satisfactions (when everything goes as planned) and frustrations (when things do not work as planned), and this necessarily leads to positive or negative emotions. Some emotions (such as happiness, pleasure, delight, thrill, and zeal) act to potentially enhance learning and optimize student achievement. Inclusion of affect and emotions in the classroom leads to an environment that is more in consonance with the history of science and the practice of science. The best solution to resolve this dilemma is perhaps through interactions among peers and also between the students and the teachers.

7.16 Scientific Method and Objectivity

The scientific method continues to be problematic in both science and science education, as it is generally believed that use of the scientific method ensures objectivity and the universality of science. To recognize that science is not culture-free is indeed a humbling experience for scientists. Gerald Holton (2014) recalling why he decided that Harvard Project Physics be based on a humanistic approach stated, "I based my decision in part on the hunch that more beginning students would come to take this course, to learn not only that *F* is equal to *ma*, but also that science is a fascinating part of human culture" (p. 1876). History of science shows that no set of objective rules or method can explain theory choice sufficiently. A scientist needs considerable experience to know under what circumstances and in what way any posited rules (formulated a priori) should be applied. Some science teachers believe that use of creativity and imagination (i.e., lack of a scientific method) during the interpretation phase of the data may compromise the objectivity of the scientists. On the contrary, history of science shows that it is precisely during the interpretation of the data that scientists need to be more creative. Lack of an understanding of the scientific enterprise (science in the making) that involves ambiguity, uncertainty, and intuitiveness (among other aspects) leads science educators and textbooks to emphasize the importance of the scientific method. Situating scientific inquiry in the context of "science in the making" leads to understanding complex and controversial subjects (such as evolutionary theory) more fruitful and even shows the problematic nature of progress in science. For example, students may think that Darwinism is not really a science at all but instead a worldview.

7.17 Social Interactions and the Evolving Nature of Objectivity

Social dimensions of science (e.g., peer-review process and interactions among members of the scientific community) facilitate the transition from a subjective to a more objective nature of scientific knowledge. Within this perspective, recognition of the social character of inquiry espouses pluralism, and acknowledges explanatory pluralism (Longino, 2002). Similarly, Giere (2006b) has recommended a pluralism of perspectives and that knowledge claims are perspectival rather than absolutely objective and hence cannot provide a "true" or "correct" answer to a problem. Pretensions of science to objectivity need to be countered with the social dimensions of knowledge. Errors in science are corrected by communication, first within the research group and later within the wider scientific community. In other words, objectivity in its purest sense is perhaps never an option, and is best understood within a social perspective based on sharing and communicating ideas. It is not the dualistic separation of objective and subjective knowledge (e.g., rational and creative, researcher, and researched) but rather the specific, social, cultural, and sociopolitical contexts that facilitate progress in science. Recent work on the life of Charles Darwin has shown that his theory of evolution was inextricably linked with its social dimensions. Knowledge is achieved primarily through a process of inquiry that is characterized by its social, experimental, and fallible nature. Nevertheless, it is not necessarily the experimental data (Baconian orgy of quantification) but rather the diversity/plurality of ideas in a scientific discipline that contributes toward a better understanding of the evolving nature of objectivity. In essence, the pluralist approach dissolves the distinction between the epistemic and the social (Longino, 1990) and thus helps to correct flaws and enhance the reliability of scientific results. Although within Marxism the influence of social factors is important, instead in Mainland China Mao's concept of "practice" is highly valued. The role of social factors and the scientific community is important and at times objectivity may become synonymous with consensus. History of science, however, shows that there is no guarantee that the scientific community is infallible (cf. Rowlands, Graham, & Berry, 2011). All knowledge develops and forms part of the social, cultural, and local milieu. Given appropriate social interactions, the idea of localness can transcend and facilitate trans-localness, which leads to greater objectivity. In this context, Daston and Galison's (2007) concept of the evolving nature of objectivity, which facilitates the different forms of objectivity (scientific judgment) to coexist and even perhaps compete.

7.18 Theory-Laden Observations and Objectivity

The role of theory-laden observations is important as school science fosters the idea that experimental observations are entirely objective. History of science provides many intriguing episodes. For example, in the 1919 solar eclipse expedition, if Edington had not been aware of Einstein's special theory of relativity, it would have been extremely difficult to interpret the observations. In this context data obtained by students in an experiment can provide grounds for relating the experimental observations and students' prior beliefs. Experiments are difficult to conduct and can provide evidence for more than one hypothesis, and students are generally unaware of this possibility.

7.19 Transgression, Objectivity and Scientific Progress at a Crossroads

This section is primarily based on results reported in Chap. 6 (based on general chemistry textbook evaluations) and following are some of the salient features:

(a) Due to the controversies and interactions among members of the scientific community, objectivity itself is achieved partially, progressively, in degrees, and hence the need for "transgression of objectivity."
(b) If objectivity is achieved in degrees it is plausible to suggest that the scientific method based on a series of rigid steps cannot characterize the scientific endeavor.

(c) As the word "method" itself denotes a more structured approach to science, it is preferable instead to emphasize the work of scientists themselves within a historical context.
(d) It is important to note that even before the Scanning tunneling microscopy (STM) was invented, scientists (e.g., Dalton and many others) were trying to understand atomic structure through indirect experiments (cf. Hoffmann, 2012). This shows that the quest for knowledge/understanding of matter has a long history, starting perhaps with magnifying glasses in the fifteenth century.
(e) Presentations of some textbooks give the impression that STM provides actual photographs of the atoms, whereas in actual practice the images are computer generated.
(f) STM and Atomic force microscopy (AFM) investigate only surface atoms and do not provide information with respect to internal structure of atoms.
(g) STM can be used only for conductive surfaces, whereas AFM can be used with almost any surface.
(h) Some textbooks raised the question: are atoms real? And that we can now "see" atoms and also their magnifications (up to 10 million times). It is plausible to suggest that if atoms are real that refers to "representation," and "seeing" and the magnifications to "presentation"—thus scientific progress is at a crossroads. In other words, the balance has shifted toward presentation that facilitates intervention (nanotechnology).
(i) Some textbooks emphasized the production of new materials based on nanotechnology that were previously even difficult to dream of, such as: C_{60}, buckminsterfullerene, the third form of carbon; artificial cells that can provide additional oxygen to the bloodstream; miniaturizing of electrical instruments (cell phones, computers); waterproof and wrinkle-free nanoparticle based textile products; nanoscale materials that are highly conductive (e.g., gold, which is otherwise not a conductor) and some even 40 times stronger than steel; hydrogen absorbed into nanotubes would solve the problems associated with hydrogen fuel cells; and enormous surface to volume ratio of nanomaterials is of special importance for the drug industry.

These innovations in nanotechnology provide examples of cutting-edge research that is at a crossroads with our existing state of knowledge, and even perhaps seem to belong to the realm of science fiction. However, as suggested by Hoffmann (Email to author, February 24, 2016b) a word of caution is necessary in understanding the significance and future prospects of nanotechnology.

7.20 Uncertainty and Objectivity

In classroom practice positivism imbues scientific knowledge with a Laplacian certainty denied to all other disciplines. This leads to teaching science by neglecting the social and cultural milieu in which scientists work and the certainty surrounding science is conveyed as a dogma. According to *Project* 2061: "The notion that scientific knowledge is always subject to modification can be difficult for students to grasp. It seems to oppose the certainty and truth popularly accorded to science, and runs counter to the yearning for certainty that is characteristic of most cultures, perhaps especially so among youth" (AAAS, 1993, p. 5). Actually, in students' processes of construction of knowledge uncertainty can help to advance the learning process. The knowledge that has already been acquired allows the researchers to raise new questions because there is uncertainty in existing knowledge. The dynamics of uncertainty and raising new questions helps to facilitate greater understanding. Based on Piaget's genetic epistemology, constructivism emphasizes the inherent uncertainty of the constructed knowledge of the world by both children and scientists. Furthermore, the concept of "objectivity" is reconceptualized as consensual agreement among scientific communities of practices, quite similar to what Daston and Galison (2007) have referred to as "trained judgment."

7.21 Is Objectivity an Opiate of the Academic?

In the light of the results presented in this book, it is important to consider the following thesis put forward by Aikenhead (2008): "Given the prominence of the objectivity/subjectivity dichotomy in science education and most of its research, many academics must feel comfortable with the dichotomy, so much so that I wonder if objectivity has become the opiate of the academic" (p. 584). This is a controversial thesis and perhaps many science educators may consider it to be too radical and extreme. Nevertheless, let us reconsider the results reported in this book in order to have a better perspective. Chap. 6 showed that almost 90% of general chemistry textbook authors (published in USA) did not recognize the problematic nature of objectivity and again about half endorsed the traditional step-wise scientific method. About one-third of the authors of articles written by science education researchers (Chaps. 3–5) did not recognize the problematic nature of objectivity. Given this state of affairs and perhaps with some reluctance, I would like to endorse Aikenhead's (2008) thesis, namely "objectivity as an opiate of the academic." Lest it be misconstrued, my objective (as part of the science education community) in raising this issue is that of a constructive criticism and a call for a critical appraisal of how we do and understand science, while trying to grasp the evolving nature of objectivity. At this stage it is important to note that after reading a preliminary version of this chapter, Aikenhead (personal communication, July 27, 2016) suggested the following: "It would be interesting to read a parallel chapter to your Chap. 7 from the standpoint of subjectivity. On pages 9–10 you explore the two poles of a continuum. In 1991, I published a grade 10 STS science textbook *Logical Reasoning in Science and Technology*, in which objectivity was replaced by the notion of degrees of subjectivity. Thus, the value that guides scientists is to reach the lowest level of subjectivity as humanly and financially possible. This stance makes intuitive sense to high school students, and it eliminates many of the issues that arise in Chap. 7 about the problems with objectivity" (underline added). The notion of "degrees of subjectivity" can be compared to what Machamer and Wolters (2004, pp. 9–10) have referred to as "objectivity comes in degrees." In a similar vein Daston and Galison (2007, p. 374) have pointed out that, "subjectivity is not a weakness of the self, [but rather] it is the self." For a science educator it is important to understand that the notions of subjectivity and objectivity are intricately intertwined and it is the constant struggle between these two poles of a continuum that facilitates progress in science.

Finally, it is concluded that the evolving nature of objectivity is important for science education as school and college science generally simplify complex historical episodes under the rubric of objectivity without really understanding that the underlying issues perhaps are dependent on trained judgment (Daston & Galison, 2007). Although, achievement of objectivity in actual scientific practice is a myth, it still remains a powerful and useful idea (Harding, 2015). Similarly, Aikenhead and Michell (2011) have endorsed a similar approach: "Consensus making *reduces* the subjectivity of individual scientists or teams of scientists. Consequently, a realistic goal for scientists is *low subjectivity*. The public storyline that scientists attain objectivity is a myth …. The ideal of objectivity fails in the reality of practice …. Nevertheless, objectivity remains a powerful and useful ideal" (p. 41, underline added). Despite a critical stance toward the role played by objectivity, it is important to note that scholars of different disciplines and persuasion still consider it to be a useful epistemic virtue (e.g., Aikenhead, Daston, Galison, Harding, Hodson, Hoffmann, & Machamer). It is essential that science educators debated these epistemic virtues in order to clarify what they entail and thus facilitate a better understanding of the dynamics of scientific progress.

7.22 Educational Implications

Based on different chapters of this book, here I summarize the following educational implications that can facilitate the work of both students and teachers:

- Studying controversies in their original scientific/historical context of inquiry can facilitate a perspective that can help to question objectivity in different topics of the science curriculum.
- Differentiating between scientists' theory and historians' theory can provide a better understanding of how the evolving nature of objectivity is crucial for following scientific progress.
- Despite the importance of experimental data scientists can still interpret the same data differently. This shows that experimental data do not necessarily facilitate objectivity in science.
- Experimental facts remain mute unless an attempt is made to interpret them, which leads to the elaboration of a narrative that facilitates understanding.
- Pluralism of perspectives (Giere, Longino) helps to correct flaws and thus enhance the reliability of scientific results. Pluralism based on value-judgments

is a virtue rather than a liability. Recognizing and evaluating value-laden science is important for understanding progress.

- The need to understand objectivity more as a process rather than an end product. For Piaget a process consists of successive approximations toward objectivity, and furthermore objectivity comes in degrees (Daston, Galison, Machamer, & Wolters).
- Articulation of tacit knowledge (Polanyi) in contrast to rigid rules and algorithms is more helpful in understanding objectivity.
- Differentiation between algorithmic and conceptual teaching strategies. Algorithmic strategies are based on adherence to rigid rules and procedures that approximate to mechanical objectivity. In contrast, conceptual strategies can generate cognitive conflicts and thus are open to negotiation of meaning that is trained judgment.
- Tentative nature of science is an important characteristic of nature of science. For example, atomic models have changed over the last 200 years (Dalton, Thomson, Rutherford, Bohr, Sommerfeld, wave mechanical). It is plausible to suggest that the tentativeness of science manifests itself in the evolving nature of objectivity. For example, at some stage in history all atomic models were considered to be objective, especially to its proponents. Teaching tentativeness of science in the context of the evolving nature of objectivity can facilitate a better understanding of scientific progress.
- School science generally associates and emphasizes certainty and objectivity with progress in science. However, it can be argued that lack of certainty can be used as a means to facilitate conceptual understanding. Acquired knowledge raises further questions that need research and hence show uncertainty, which can drive the learning process of acquiring knowledge.
- Given the evolving nature of objectivity it is important that teachers consider themselves also as learners and that their constructions (classroom interventions) of knowledge are never complete but rather tentative.
- In the history of science one form of objectivity did not supplant the other, but rather the two coexisted. Consequently, it is plausible to suggest that classroom discussions could provide an opportunity to facilitate and understand the objectivity–subjectivity continuum.

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