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Chapter 30
New Directions for Nature of Science Research

Gürol Irzik and Robert Nola

30.1 Introduction

Calls for the inclusion of the nature of science (NOS for short) into science education have a long history. A number of distinguished scientists, philosophers and education theorists such as John Dewey, James Conant, Gerald Holton, Leo Klopfer, Joseph Schwab, James Robinson, James Rutherford, Michael Martin, Richard Duschl, Derek Hodson, Norman Lederman, Michael Matthews and Norman McComas throughout the twentieth century emphasised the importance of teaching science's conceptual structure and its epistemological aspects as part of science education (Matthews 1998a; McComas et al. 1998). Today, science education curriculum reform documents in many parts of the world underline that an important objective of science education is the learning of not only the content of science but its nature.[1] The rationale is that scientific literacy requires an understanding of the nature of science, which in turn facilitates students' learning of the content of science, helps them grasp what sort of a human enterprise science is, helps them appreciate its value in today's world and enhances their democratic citizenship, that is, their ability to make informed decisions, as future citizens, about a number of controversial issues such as global warming, how to dispose nuclear waste, genetically modified food and the teaching of

[1] See, for example, American Association for the Advancement of Science (1990, 1993), Council of Ministers of Education (1997), National Curriculum Council (1988), National Research Council (1996), Rocard et al. (2007), and McComas and Olson (1998).

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intelligent design in schools.[2] Allchin expressed this idea succinctly: 'Students should develop an understanding of how science works *with the goal of interpreting the reliability of scientific claims in personal and public decision making*' (Allchin 2011, p. 521; emphasis original).

There is a voluminous literature on what NOS is, how to teach it and what views of NOS students and teachers hold. The aim of this chapter is not to review this literature. The interested reader can refer to other chapters of this handbook and earlier useful surveys (Abd-El-Khalick and Lederman 2000; Deng 2011 and others; Lederman 2007). Teachers' and students' views of NOS are also beyond the scope of this chapter, in which we focus exclusively on what NOS is. In the next section we summarise the consensus NOS theorising in science education has produced. Making use of the existing consensus, we then provide, in Sect. 30.3, a structural description of all the major aspects of science in terms of eight categories. Applying the idea of family resemblance to these categories, we obtain what we call 'the family resemblance approach'. We articulate it in some detail in Sect. 30.5. We believe that the family resemblance approach provides a systematic and unifying account of NOS. We discuss this and other virtues of the family resemblance approach in Sect. 30.6. We end the chapter by making some suggestions about how to use this approach in the classroom.

We would like to emphasise that the present chapter does not deal with empirical matters such as what teachers and pupils might understand of NOS. Rather, our task is one within the theory of NOS: it is to provide a new way of thinking about what is meant by the 'nature of science'. Nevertheless, we do hope that theorists of science education and science teachers familiar with NOS discussions will find our approach not only theoretically illuminating but also pedagogically useful.

30.2 Consensus on NOS

NOS research in the last decade or so has revealed a significant degree of consensus amongst the members of the science education community regarding what NOS is and which aspects of it should be taught in schools at the precollege level. This consensus can be highlighted as follows.

Based on considerations of accessibility to students and usefulness for citizens, Lederman and his collaborators specified the following characteristics of NOS:

- Scientific knowledge is empirical (relies on observations and experiments).
- Is reliable but fallible/tentative (i.e. subject to change and thus never absolute or certain).
- Is partly the product of human imagination and creativity.

[2] This point is commonly made, for example, in Driver et al. (1996), McComas et al. (1998), Osborne 2007, and Rutherford and Ahlgren (1990).

- Is theory-laden and subjective (i.e. influenced by scientists' background beliefs, experiences and biases).
- Is socially and culturally embedded (i.e. influenced by social and cultural context).[3]

They also emphasised that students should be familiar with concepts fundamental to an understanding of NOS such as observation, inference, experiment, law and theory and be also aware of the distinctions between observing and inferring and between laws and theories and of the fact that there is no single scientific method that invariably produces infallible knowledge. Others added that science is theoretical and explanatory; scientific claims are testable and scientific tests are repeatable; science is self-correcting and aims at achieving values such as high explanatory and predictive power, fecundity (fruitfulness), parsimony (simplicity) and logical coherence (consistency) (Cobern and Loving 2001; Smith and Scharmann 1999; Zeidler and others 2002).

A number of researchers propose a similar list of characteristics by studying the international science education standards documents. These documents also indicate substantial consensus on two further matters: the ethical dimension of science (e.g. scientists make ethical decisions, must be open to new ideas, report their findings truthfully, clearly and openly) and the way in which science and technology interact with and influence one another (McComas et al. 1998; McComas and Olson 1998). Based on a Delphi study of an expert group consisting of scientists, science educators and science communicators, philosophers, historians and sociologists of science, Osborne and others (2003) found broad agreement on the following eight themes:

- Scientific method (including the idea that continual questioning and experimental testing of scientific claims is central to scientific research)
- Analysis and interpretation of data (the idea that data does not speak by itself, but can be interpreted in various ways)
- (Un)certainty of science (i.e. scientific knowledge is provisional)
- Hypothesis and prediction (the idea that formulating hypotheses and drawing predictions from them in order to test them is essential to science)
- Creativity in science (the idea that since scientific research requires much creativity, students should be encouraged to create models to explain phenomena)
- Diversity of scientific thinking (the idea that science employs different methods to solve the same problem)
- The historical development of scientific knowledge (i.e. scientific knowledge develops historically and is affected by societal demands and expectations)
- The role of cooperation and collaboration in the production of scientific knowledge (i.e. science is a collaborative and cooperative activity, as exemplified by teamwork and the mechanism of peer review).

[3] See Abd-El-Khalick (2004), Abd-El-Khalick and Lederman (2000), Bell (2004), Khishfe and Lederman (2006), Lederman (2004, 2007). Note that all of these characteristics pertain to scientific knowledge. For that reason, Lederman suggested replacing the phrase 'nature of science' with 'nature of scientific knowledge' in his recent writings (Lederman 2007).

Wong and Hodson (2009, 2010) came up with very similar themes (but with slightly different emphasis) on the basis of in-depth interviews with well-established scientists from different parts of the world who worked in different fields:

- Scientific method (different disciplines employ different methods of investigation)
- Creativity in science (creative imagination plays an important role in every stage of scientific inquiry from data collection to theory construction, and absolute objectivity in the sense of freeing oneself from biases completely is impossible)
- The importance of theory in scientific inquiry (scientific activity is highly theoretical)
- Theory dependence of observation (scientific data is theory laden and can be interpreted in various ways)
- Tentative nature of scientific knowledge (science does not yield certainty)
- The impact of cultural, social, political, economic, ethical and personal factors on science (such factors greatly influence the direction of scientific research and development and may cause biased results and misconduct) and the importance of cooperation, peer review and shared norms (such as intellectual honesty and open mindedness) in knowledge production

The overlap between the findings of these studies indicates a substantial consensus regarding NOS amongst education theorists. However, there has been some debate as to whether processes of inquiry (such as posing questions, collecting data, formulating hypotheses, designing experiments to test them) should be included in NOS. While Lederman (2007) suggested leaving them out, other science education theorists disagreed arguing that they constitute an inseparable part of NOS (Duschl and Osborne 2002; Grandy and Duschl 2007). Indeed, research summarised in the above two paragraphs do cite processes of inquiry as an important component of NOS.

Of course, much depends on how the various aspects and themes of NOS are spelled out. Osborne and his collaborators warn that various characteristics of NOS should not be taken as discrete entities, so they emphasise their interrelatedness (Osborne and others 2001, 2003, p. 711). In a similar vein, others note that blanket generalisations about NOS introduced out of context do not provide a sophisticated understanding of NOS (Elby and Hammer 2001; Matthews 2011); rather, the items within NOS ought to be elucidated in relation to one another in 'authentic contexts'. Accordingly, many science educators have called for 'an authentic view' of science, which aims to contextualise science and focuses on science-in-the-making by drawing either on science-technology-society (STS) studies or on the interviews with scientists themselves about their day-to-day activities; this underlines the heterogeneity of scientific practices across scientific disciplines through historical and contemporary case studies.[4]

[4] See Ford and Wargo (2007), McGinn and Roth (1999), Rudolph (2000), Samarapungavan et al. (2006), Wong and Hodson (2009, 2010), and Wong et al. (2009).

A number of science education theorists also urged that issues arising from science-technology-society interactions, the social norms of science and funding and fraud within science all be allotted more space in discussions of NOS; a focus on these is especially pertinent when educating citizens who will often face making hard decisions regarding socio-scientific problems in today's democracies. These topics have been raised earlier in some detail (Aikenhead 1985a, b; Kolsto 2001; Zeidler and others 2002) and are receiving increasing attention in recent years, in line with calls for an authentic view of science.[5]

30.3 NOS Categories: A Structural Description

The consensus on NOS highlighted above reveals that science is a multifaceted enterprise that involves (a) processes of inquiry, (b) scientific knowledge with special characteristics, (c) methods, aims and values and (d) social, historical and ethical aspects. Indeed, science is many things all at once: it is an investigative activity, a vocation, a culture and an enterprise with an economic dimension and accordingly has many features (cognitive, social, cultural, political, ethical and commercial) (Weinstein 2008; Matthews 2011). What is needed then is a systematic and unifying perspective that captures not just this or that aspect of science but the 'whole science' (Allchin 2011). This is no easy task, and there is certainly more than one way of carrying it out. Our suggestion is to begin with a broad distinction between *science as a cognitive-epistemic system of thought and practice* on the one hand and s*cience as a social-institutional system* on the other. This distinction is actually implicit in the aspects of NOS expressed (a) through (d) above: science as a cognitive-epistemic system incorporates (a), (b) and (c), while science as a social-institutional system captures (d). We hasten to add that we intend this as an analytical distinction to achieve conceptual clarity, not as a categorical separation that divides one from the other. In practice, the two constantly interact with each other in myriad ways, as we will see.

30.3.1 Science as a Cognitive-Epistemic System

We spell out science as a cognitive-epistemic system in terms of four categories obtained by slightly modifying (a)–(c): processes of inquiry, aims and values, methods and methodological rules and scientific knowledge. We explain these categories briefly below.[6]

[5] See Sadler (2011), Weinstein (2008), Wong and Hodson (2010), Zemplen (2009); see also the special issue of the journal *Science & Education* vol. 17, nos. 8–9, 2008.

[6] For a more detailed discussion of these, see Nola and Irzik (2005, Chaps. 2, 4, 6, 7, 8, 9, and 10).

30.3.1.1 Processes of Inquiry

This includes posing questions (problems), making observations, collecting and classifying data, designing experiments, formulating hypotheses, constructing theories and models and comparing alternative theories and models (Grandy and Duschl 2007).

30.3.1.2 Aims and Values

This will include items such as *prediction*, *explanation*, *consistency*, *simplicity* and *fruitfulness*; these are amongst the well-known aims of science recognised in the science education literature, as we saw in the previous section. With regard to prediction and explanation, we would like to make two points, which the science education literature tends to neglect. First, scientists value *novel* predictions more than other kinds of predictions because novel predictions of a theory give greater support to it than those that are not (Nola and Irzık 2005, pp. 245–247). (A prediction is novel if it is a prediction of a phenomenon that was unknown to the scientists at the time of the prediction.) Second, although there are different kinds of explanations and therefore different models of explanations, all scientific explanations are naturalistic in the sense that natural phenomena are explained in terms of other natural phenomena, without appealing to any supernatural or occult powers and entities (Lindberg 1992, Chap. 1; Pennock 2011).[7]

Other aims of science include the following: *viability* (von Glasersfeld 1989), *high confirmation* (Hempel 1965, Part I), *testability* and *truth* or at least *closeness to truth* (Popper 1963, 1975) and *empirical adequacy* (van Fraassen 1980). Aims of science are sometimes called (cognitive-epistemic) values since scientists value them highly in the sense that they desire their theories and models to realise them (Kuhn 1977). Values in science can also function as shared criteria for comparing theories and be expressed as methodological rules. For example, we can say that given two rival theories, other things being equal, the theory that has more explanatory power is better than the one that has less explanatory power. Expressed as a methodological rule, it becomes, given two rival theories, other things being equal, *choose*, or *prefer*, the theory that is more explanatory. Similar rules can be derived from other values. These enable scientists to compare rival theories about the same domain of phenomena rationally and objectively (Kuhn 1977).

30.3.1.3 Methods and Methodological Rules

Science does not achieve its various aims randomly, but employs a number of methods and methodological rules. This point emerges clearly in many studies on NOS. Historically, there have been proposals about scientific method from Aristotle,

[7] See Godfrey-Smith (2003) for a succinct summary of different models of explanations in science.

Bacon, Galileo, Newton to Whewell, Mill and Peirce, not to mention the many theories of method proposed in the twentieth century by philosophers, scientists and statisticians. For many of them, deductive, inductive and abductive reasoning form an important part of any kind of scientific method. Additional methods for testing hypotheses include a variety of inductive and statistical methods along with the hypothetico-deductive method (Nola and Sankey 2007; Nola and Irzık 2005, Chaps. 7, 8, and 9). The idea of scientific methodology also includes methodological rules; these have not received sufficient attention in the science education literature. Methodological rules are discussed at length by a number of philosophers of science such as Popper (1959) and Laudan (1996, Chap. 7). Here are some of them:

- Construct hypotheses/theories/models that are highly testable.
- Avoid making ad hoc revisions to theories.
- Other things being equal, choose the theory that is more explanatory.
- Reject inconsistent theories.
- Other things being equal, accept simple theories and reject more complex ones.
- Accept a theory only if it can explain all the successes of its predecessors.
- Use controlled experiments in testing casual hypotheses.
- In conducting experiments on human subjects, always use blinded procedures.

Two general points about scientific methods and methodological rules are in order. First, although they certainly capture something deep about the nature of methods employed in science, it should not be forgotten that they are highly idealised, rational constructions. As such, they do not faithfully mirror what scientists do in their day-to-day activities; nor can they always dictate to them what to do at every step of their inquiry. Nevertheless, they can often tell them when their moves are, or are not, rational and do explain (at least partially) the reliability of scientific knowledge. Second, we presented the above rules of method as if they are categorical imperatives. This needs to be qualified in two ways. The first is that some of the rules can, in certain circumstances, be abandoned. Spelling out the conditions in some antecedent clause in which the rules can be given up is not an easy matter to do; so such rules are best understand to be defeasible in unspecified circumstances. The second is that such categorical rules ought to be expressed as hypothetical imperatives which say: rule R ought to be followed if some aim or value V will be (reliably) achieved (see Laudan 1996, Chap. 7). Often reference to the value is omitted or the rule is expressed elliptically. For example, the rule about ad hocness has an implicit value or aim of high testability. So, more explicitly it would look like: 'If you aim for high testability, avoid making *ad hoc* revisions to theories'. When rules are understood in this way, then the link between the methodological rules of category 3 and the aims of category 2 becomes clearly visible.

30.3.1.4 Scientific Knowledge

When processes of inquiry achieve their aims using the aforementioned methods and methodological rules, these processes culminate in some 'product', viz.

scientific knowledge. Such knowledge 'end products' are embodied in laws, theories and models as well as collections of observational reports and experimental data. Scientific knowledge is the most widely discussed category of NOS, as we have seen in the previous section.

30.3.2 Science as a Social-Institutional System

Science as a social-institutional system is investigated less than science as a cognitive-epistemic system, and for that reason it is harder to categorise. We propose to study it in terms of the following categories: professional activities, the system of knowledge certification and dissemination, scientific ethos and finally social values. We discuss them in some detail below, taking into account the findings of the NOS research on this topic indicated in Sect. 30.2.

As decades of science-technology-society studies have shown, science not only is a cognitive system but is, at the same time, both a cooperative and a competitive community practice that has its own ethos (i.e. social and ethical norms) and its own system of knowledge certification and dissemination. It is a constantly evolving social enterprise with intricate relationships with technology and with the rest of the society, which both influences and is influenced by it. Scientists form a tight community and are engaged in a number of professional activities, interacting both with each other and the larger public. In short, science is a historical, dynamic, social institution embedded within the larger society. Categories of science as social-institutional system can be described as follows.

30.3.2.1 Professional Activities

Scientists do not just carry out scientific research. Qua being scientists, they also perform a variety of professional activities such as attending academic meetings, presenting their findings there, publishing them, reviewing manuscripts and grant proposals, writing research projects and seeking funds for them, doing consulting work for both public and private bodies and informing the public about matters of general interest. In this way, they perform various cognitive-epistemic and social functions such as certifying knowledge and serving certain social goals. Whether they are engaged in cognitive-epistemic or professional activities, they are expected to conform to a number of social and ethical norms. We discuss these below.

30.3.2.2 The Scientific Ethos

Part of the meaning of the claim that science is a social institution is that it has its own social (institutional) and ethical norms, which refer to certain attitudes scientists are expected to adopt and display in their interactions with their fellow scientists as well as in carrying out their scientific activities. We call them 'the scientific ethos' (or, equivalently, 'the ethos of science') for convenience, a phrase coined by the famous sociologist of science Robert Merton. However, as we will see below, the scientific ethos as we understand it is not confined to what is known as the 'Mertonian norms' in the literature. Merton was one of the first to study the institutional norms of science in the 1930s and formulated some of them as follows, based on his extensive interviews with scientists (Merton 1973, Chap. 13):

- *Universalism*: Science is universal in the sense that scientific claims are evaluated according to pre-established objective, rational criteria so that characteristics of scientists such as ethnic origin, nationality, religion, class and gender are irrelevant when it comes to evaluation.
- *Organised scepticism*: Scientists subject every claim to logical and empirical scrutiny on the basis of clearly specified procedures that involve scientific reasoning, testability and methodology and suspend judgement until all the relevant facts are in and bow to no authority except that of critical argumentation.
- *Disinterestedness*: Scientists should evaluate and report their findings independently of whether they serve their personal interests, ideologies and the like. The norm of disinterestedness has the function of preventing scientists from hiding or fudging the results of their inquiries even when they go against their personal biases, interests and favoured ideology.
- *Communalism* refers to the common ownership of scientific discovery or knowledge. The rationale is that science is a cooperative endeavour: new scientific knowledge always builds upon old knowledge and that scientific discoveries owe much to open and free discussion and exchange of ideas, information, techniques and even material (such as proteins).

Although Merton arrived at these norms through an empirical study, we should not lose sight of the fact that they can be taken as both descriptive and prescriptive *qua* being norms. In other words, they tell us how scientists ought to behave, not just how they do behave when they do science. Their normative nature and power is evident from the fact that scientists often face the sanctions of the scientific community when they violate them.[8]

In time, the scientific community has become increasingly self-conscious of the norms of conduct in science, as a result of which they have proliferated and been codified under the banner 'ethical codes of conduct'. There is now a whole subfield called the 'ethics of science' devoted to this topic. Amongst other things, these norms include the following (Resnik 2007, Chap. 2):

- Intellectual honesty (or integrity): Scientists should not fabricate, distort or suppress data and should not plagiarise. They should bow to no authority except that of evidence and critical argumentation.

[8] STS scholars are generally critical of Mertonian norms and claim that there is a counter-norm for every Mertonian norm, with the implication that Mertonian norms do not guide scientific practice and therefore are simply functionless. See, for example, Sismondo (2004, Chap. 3) and the literature cited therein. However, there are also excellent critiques of these critiques such as Radder (2010).

- Respect for research subjects: Scientists should treat human and animal subjects with respect and dignity. This involves getting the informed consent of human subjects and not inflicting unnecessary pain on animal subjects and the like.
- Respect the environment: Avoid causing harm to the environment.
- Freedom: Scientists should be free to pursue any research, subject to certain constraints (e.g. as implied by the previous two ethical principles).
- Openness: Scientists should be open to free and critical discussion and to share ideas, data, techniques and even materials (such as proteins). They should be willing to change their opinion when presented with good reasons.

Today many scientific institutions (universities, academies, funding organisations, etc.) have such ethical codes which they announce on their websites.

None of this is meant to suggest that there is no misconduct, fraud, data suppression or misrepresentation and the like, or fierce competition, especially for scarce resources such as funding, which sometimes results in secrecy (the opposite of openness) in science. Scientists are not saints. Nevertheless, when they violate the norms of science, they often face sanctions. Science has developed a social mechanism of certification and dissemination to eliminate or at least reduce misconduct and promote collaboration amongst scientists.

30.3.2.3 The Social Certification and Dissemination of Scientific Knowledge

When a scientist or a team of scientists completes their research, they are hardly finished with their work. Their findings need to be published; this requires a process of peer review. When published, they become public and are now open to the critical scrutiny of the entire community of relevant experts. Only when they prove their mettle during this entire ordeal are their findings accepted into the corpus of scientific knowledge and can, amongst other things, be taught at schools. This is in a nutshell the *social* system of certification and dissemination of scientific knowledge, which involves the collective and collaborative efforts of the scientific community (Kitcher 2011, Chap. 4). This system functions as an effective *social quality control* over and above the *epistemic control* mechanisms that include testing, evidential relations and methodological considerations described in Sect. 30.3.1. They jointly work to help reduce the possibility of error and misconduct.

30.3.2.4 Social Values of Science

Science embodies not only cognitive-epistemic values but also social ones. Some of the most important social values are freedom, respect for the environment and social utility broadly understood to refer to improving people's health and quality of life as well as to contributing to economic development. Without sufficient freedom of research, scientific development would be stifled. Respect for the environment involves both the negative duty of not damaging it and the positive duty of protecting it by saving biodiversity and reducing carbon emissions that cause climate change. As a species we are unlikely to survive if we do not respect the environment. Science that does not contribute to better lives for people would not enjoy their support; the social legitimation of science today depends crucially on its social utility. Social utility then serves as an important social goal of science.

This completes our description of the eight categories of science which can be tabulated as below.

Science							
Science as a cognitive-epistemic system				Science as a social system			
1	2	3	4	5	6	7	8
Processes of inquiry	Aims and values	Methods and methodological rules	Scientific knowledge	Professional activities	Scientific ethos	Social certification and dissemination of scientific knowledge	Social values

Although we believe that the categories that make up science as a cognitive-epistemic system are pretty exhaustive, we admit the possibility that other categories might perhaps be added or new categories might emerge as science develops. We do not think, however, that categories of science as a social system is exhaustive in any way. Nor do we claim that this is the only or the best way of describing science as a social system. Others may carve it out differently. Nevertheless, we do believe that it captures an important part of science as social practice. Similarly, we do not pretend to have listed all the items that fall under each of the eight categories above. In fact, we consider them open-ended; that is, the characteristics of science that fall under each category are not fixed and develop historically. Overall, we believe that the eight categories capture the structural features of NOS in a systematic and comprehensive way.

30.4 Clarifying the Meaning of 'Nature of Science' and the Idea of Family Resemblance

Although we suggested that the above eight categories characterise nature *of science*, we have not explored the meaning of term 'nature' that occurs in that phrase. What do we mean by '*nature* of science'? To our knowledge, this is a question that is hardly raised in the science education literature. Here we briefly mention three conceptions of what such a nature might be.

First, the *nature* of science could be taken to be the specification of a natural kind of thing which has an essence, where an essence is a set of properties which a thing *must* have and without which it is *not possible* for that thing exist and to be that *kind* of thing. Triangles have an essence in this sense, but it is very doubtful that science has an essence of this sort. We can agree with Rorty's negative answer to the title of his paper 'Is natural science a natural kind?' (Rorty 1991, pp. 46–62).

A second suggestion about 'nature' is to claim that it is a (small) set of necessary and sufficient properties that something should possess if it is to be deemed science. Here strong modal claims found in the essentialist approach mentioned above are downplayed or eschewed in favour of the mere possession of the set of features shared by all sciences and only by them. However, so far all attempts to define science in terms of necessary and sufficient conditions have failed. Some have restricted their approach to the nature of science by focusing narrowly on just the fourth category of science, viz. scientific knowledge, and then have attempted to define what is to count as science as what is verifiable (some positivists) or what is falsifiable (Popper) and so on.[9] This is not the approach we advocate here in characterising science.

A third approach might be simply to list a number of items falling under the concept of science without pretending to give a set of necessary and sufficient properties or to specify essence for science. Thus one common approach to the *nature* of science in science education lists some salient features of science as in Sect. 30.2. This is also the approach we have adopted by setting out the eight categories of science and listing the items that fall under each. However, there is a problem to be tackled: not all sciences share these features or items all at once. Indeed, a number of science education theorists have drawn attention to important differences amongst scientific disciplines (Samarapungavan et al. 2006; Wong and Hodson 2009). If some sciences lack some of the features others share, what justifies the label 'science' for them? Merely providing a list of preferred items is powerless to answer this question.

Luckily, there is a satisfactory answer within philosophy that invites one to have a quite different approach to what counts as a 'nature' in talk of 'NOS'. In fact it takes us well away from the three ways of understanding 'nature' listed above in using the important idea of family resemblance (Eflin and others 1999; Hacking 1996; Dupre 1993). In a nutshell, the nature of science consists of a set of family resemblances amongst the items that fall under the eight categories of science. In an earlier article, we articulated this approach in some detail for the purposes of science education (Irzik and Nola 2011). In this chapter, we develop it further.

The idea of family resemblance was developed by the philosopher Ludwig Wittgenstein in recognition of the fact that not all terms can be defined in terms of necessary and sufficient conditions or by specifying essences or natures (Wittgenstein 1958, Sects. 66–71). To see this, compare 'triangle' with 'game'. The former can be defined explicitly as a closed plane figure with three straight sides. This definition not only gives six characteristics that specify the necessary and sufficient conditions for being a triangle but also determines the 'essence' of being a triangle or the analytic meaning of the term 'triangle'. In this definition, those properties that are shared by all triangles and only by triangles are specified explicitly. By contrast,

[9] See some of the following who may be, in addition, critical of the idea of the demarcation of science from non-science but whose focus in so doing is just upon the fourth category, viz. what is to count as a scientific statement: (Alters 1997; Hacking 1996; Laudan et al. 1986; Stanley and Brickhouse 2001; Ziman 2000).

Wittgenstein argued, the term ‘game’ cannot be defined in this way. Any attempt to define the term ‘game’ must include games as different as ball games, stick games, card games, children’s games that do not involve balls, sticks or cards (such as tag or hide-and-seek), solo games (hopscotch) and mind games. Unlike the term ‘triangle’, there is no fixed set of necessary and sufficient conditions which determine the meaning of ‘game’ and thus no set of properties that cover all games and at the same time admit nothing which is not a game.[10] Nevertheless, Wittgenstein argued, all games form ‘a family resemblance’, forming a complicated network of similarities, overlapping and criss-crossing. It is these similarities that justify the use of the term ‘game’ to all those diverse activities from baseball to hopscotch.

Consider a set of four characteristics {A, B, C, D}. Then one could imagine four individual items which share any three of these characteristics taken together such as (A&B&C) or (B&C&D) or (A&B&D) or (A&C&D); that is, the various family resemblances are represented as four disjuncts of conjunctions of any three properties chosen from the original set of characteristics. This example of a polythetic model of family resemblances can be generalised as follows. Take any set S of n characteristics; then any individual is a member of the family if and only if it has all of the n characteristics of S, or any (n-1) conjunction of characteristics of S, or any (n-2) conjunction of characteristics of S, or any (n-3) conjunction of characteristics of S and so on. How large n may be and how small (n-x) may be is something that can be left open as befits the idea of a family resemblance which does not wish to impose arbitrary limits and leaves this to a ‘case by case’ investigation. In what follows we will employ this polythetic version of family resemblance (in a slightly modified form) in developing our conception of science.

Consider the following limiting case. Suppose an example like that above but in which there is a fifth characteristic E which is common to all the disjunctions of conjunctions as in the following: (A&B&C&E) or (B&C&D&E) or (A&B&D&E) or (A&C&D&E). Would this be a violation of the kind of family resemblance definition that Wittgenstein intended? Not necessarily. We might say as an example of characteristic E in the case of games that games are at least activities (mental or physical). Nevertheless, being an activity is hardly definitional of games, nor does it specify a criterion of demarcation; there are many activities that are not games, such as working or catching a bus.

We will see in the case of science that there are characteristics common to all sciences, but are such that they cannot be definitional of it. They cannot be used for demarcating science from other human endeavours either. An example would be observing. We cannot think of a scientific discipline which does not involve making or relying on observations at some point. But then not everything that involves observing is a science (such as being observant when crossing a road in heavy traffic). Similarly, we cannot think of a science that does not involve making some

[10] John Searle has disputed this example, arguing that ‘game’ can be defined as follows: a series of attempts to overcome certain obstacles that have been created for the purpose of overcoming them (Searle 1995, 103). However this dispute is resolved, there might still be other cases where the family resemblance idea gets some traction, as we think it does in the case of the term ‘science’.

kinds of inference at some point; if it did not, it would not get beyond naive data collecting. Nevertheless, as before, inferring, though common to the sciences, is not exclusive to them. Judges in a court or speculators on the stock market make inferences as well, but they are not doing science.

In the light of these points we can say that there are a few core characteristics that all sciences share (collecting data and making inferences, for instance). Nevertheless, even though they are generic, they are not sufficient either to define science or to demarcate it from other human endeavours. It is the other characteristics that accompany observing and inferring that make an important contribution to the family-forming characteristics that characterise scientific disciplines. It is this modified version of polythetic family resemblance that we will employ in what follows.

30.5 The Family Resemblance Approach to Science

There are many items called ‘science’, ranging from archaeology to zoology. (Here we will exclude the special case of mathematics from our discussion because of its non-empirical character.) So what do these many things called ‘science’ have in common? The idea of family resemblance will tell us that this is a wrong question to ask. What we need to do is to investigate the ways in which each of the sciences are similar or dissimilar, thereby building up from scratch polythetic sets of characteristics for each scientific discipline. The science categories we have introduced in Sect. 30.3 will come in handy for this task.

Begin with the items data collecting, making inferences and experimenting that fall under the category ‘processes of inquiry’. Although all disciplines employ the first two and most (such as particle physics and chemistry) are experimental, there are a few disciplines that are not. Astronomy and earthquake science are cases in point since experiments are simply impossible in these fields. We cannot manipulate celestial objects; nor can we carry out experiments in earthquake science by manipulating earthquakes (though there are elaborate techniques for seismic detection which are not strictly experimental in the sense of experimentation as manipulation that we intend). Consider next the category ‘aims and values’ and the item prediction falling under it. Again, most sciences aim to make predictions, especially novel ones, but not all of them succeed. For example, astronomy is very good indeed in predicting planetary positions. In contrast, even though earthquake science does a good job of predicting the approximate locations of earthquakes, it fails badly with respect to predicting the time of their occurrence. Medicine can statistically predict the occurrence of many diseases under certain conditions without being able to tell who will develop them and when.

Let us now explore the similarities and differences amongst various scientific disciplines in terms of the items under the category ‘methods and methodological rules’. Many sciences employ the hypothetico-deductive method, which can be roughly described as drawing out observable consequences of theories and then checking them against observational or experimental data. For example, particle physics and earthquake science use this method, but there does not appear to be any place for randomised double-blind experiments in these disciplines. In contrast, in evidence-based clinical medical science, the hypothetico-deductive method appears not to be of common use, while the methods of randomised double-blind experiments are the ubiquitous gold standard for testing. Similarly, some very important scientific research projects like sequencing the human genome do not involve much hypothesis testing, but rather are data-driven, inductive inquiries where most of the work is done by computer technologies.

Finally, consider the category of scientific knowledge and the items like laws, theories and models that fall under them. The idea of family resemblance applies here as well since not all sciences may have laws. For example, while there are clearly laws in physics, it is a contested issue as to whether there are laws in biology (Rosenberg 2008).

In the above we have mentioned a number of individual sciences and a number of characteristics. As can be seen for any chosen pair of these sciences, one will be similar to the other with respect to some of these characteristics and dissimilar to one another with respect to other characteristics. If we think of these characteristics as candidates for defining science, then no definition in terms of necessary and sufficient conditions would be forthcoming. If we take a family resemblance approach, however, things look very different and promising. To see this more concretely, let us represent data collection, inference making, experimentation, prediction, hypothetico-deductive testing and blinded randomised trials as D, I, E, P, H and T, respectively. Then we can summarise the situation for the disciplines we have considered as follows:

$$\begin{aligned}&\mathit{Astronomy} = \{D, I, P, H\}; \mathit{Particle\ physics} = \{D, I, E, P, H\};\\&\mathit{Earthquake\ science} = \{D, I, P', H\}; \mathit{Medicine} = \{D, I, P'', E, T\},\\&\text{where } P' \text{ and } P'' \text{ indicate differences in predictive power as indicated.}\end{aligned}$$

Thus, none of the four disciplines has all the six characteristics, though they share a number of them in common. With respect to other characteristics, they partially overlap, like the members of closely related extended family. In short, taken altogether, they form a family resemblance.

Note that in order to convey the core idea that 'science' is a family resemblance concept, we have so far considered characteristics of science understood only as a cognitive-epistemic system. Does the idea of family resemblance apply to science as a social-institutional system as well? We believe that it does, at least to some degree. All scientific disciplines have a peer review system and a system of knowledge certification and dissemination. However, not all of them share exactly the same social values or the same elements of the scientific ethos. For example, the norm 'respect human and animal subjects' would not apply to disciplines such as physics and chemistry that do not deal with human and animal subjects, but 'avoid damaging the environment' certainly would. Similarly, although many sciences serve social utility, there are some fields (such as cosmology and parts of particle physics such as unified field theory) that are not obviously socially useful in any way; they are practised merely to satisfy our curiosity about the workings of nature. In short, the sciences form a polythetic family resemblance set with respect to their social and ethical dimensions as well.

30.6 Virtues of the Family Resemblance Approach

We believe that the family resemblance approach to science has several virtues, both theoretical and pedagogical. Perhaps the most important theoretical virtue of this approach is the systematic and comprehensive way it captures the major structural features of science and thereby accommodates, in a pedagogically useful way, almost all of the findings of NOS research in science education summarised in Sect. 30.2. As we shall illustrate in the next section, both the categories themselves and the items that fall under them do not dangle in the air as discrete entities; rather, they are tightly related to each other in a number of ways, forming an integrated whole. Thus, we can say that

> Science is a cognitive and social system whose investigative activities have a number of aims that it tries to achieve with the help of its methodologies, methodological rules, system of knowledge certification and dissemination in line with its institutional social-ethical norms, and when successful, ultimately produces knowledge and serves society.

This generic description is not meant as a definition of science, but rather as indicating how various aspects of science can be weaved together systematically as a unified enterprise.

By including science as a social institution as part of the family resemblance approach, the social embeddedness of science emphasised in the NOS literature in science education is captured in a novel way. A significant part of what it means to say that science is socially embedded is to say that noncognitive values are operative in science and influence science. No social institution, not even science, exists in a vacuum, so all kinds of social, cultural, historical, political and economic factors may influence it. Just to give an obvious example, funding strongly affects the choice of scientific problems and research agendas. Noncognitive factors of all sorts (gender biases, ideologies, economic considerations, etc.) may influence data description, hypotheses and even evidential relations in certain areas such as primatology and research on sex differences, as noted by feminist scientists and philosophers (Longino 1990). Sometimes these factors may cause scientists to deviate from the ethical norms of science (they may, e.g. fabricate or suppress data) and thus have a distorting effect on scientific conduct. However, not all social factors have a negative impact on science. Indeed, one of the most important functions of the ethos of science and mechanisms like peer review along with open and free critical discussion is precisely to minimise the negative effects on science. The ethos of science and the social system of scientific knowledge production contribute to the reliability of scientific knowledge as much as scientific methods and methodological rules do.

In practice, scientific inquiry is always guided by both cognitive-epistemic and social-institutional 'rules of the game', so to speak. This gives substance to our earlier claim that the distinction between science as a cognitive-epistemic system and science as a social institution is a conceptual one introduced for analytical purposes; but in practice the two are inseparable.

The historical, dynamic and changing nature of science can be accommodated naturally by the family resemblance approach through its open-ended categories that allow for the emergence of new characteristics of science within each category. For example, from a historical perspective we see that many scientific disciplines such as physics, chemistry, electricity and magnetism became mathematical only after the scientific revolution that occurred in the sixteenth and seventeenth centuries. Similarly, the hypothetico-deductive method was first clearly formulated and became established during the same period. New methodological rules like the one that tells the scientist to use blind procedures in conducting experiments on human subjects in life sciences came about only in the twentieth century. So did many ethical norms of science. The family resemblance approach therefore incorporates the dynamic, open-ended nature of science.

A unique virtue of the family resemblance approach is that it does justice to the differences amongst scientific disciplines and yet at the same time explains their unity by emphasising the similarities and partial overlaps amongst them. It is the existence of these 'family ties' that justify the label 'science' that we apply to various disciplines from archaeology to zoology. The unity of science is a unity-within-diversity. Earlier we pointed out that observing and inferring are common to all scientific disciplines even though they are not unique to the sciences. Another particularly important common feature of all scientific disciplines is the naturalism inherent in them—a feature that has not received sufficient attention in the NOS literature. We have touched upon this in discussing the notion of scientific explanation in Sect. 30.3.1 and are now in a position to articulate it more fully.

Science appeals to only natural entities, processes and events; its mode of explanation, aims and values, ethos, methods and methodological rules and the system of knowledge certification contain nothing that is supernatural or occult. Scientific naturalism is not an addendum to science invented by philosophers; rather, it is inherent to science. As Robert Pennock aptly puts it, it is a 'ground rule' of science so basic that it seldom gets mentioned explicitly (Pennock 2011, p. 184). One of the important science reform documents that does draw attention to this aspect of science is the National Science Teachers Association's statement on NOS: 'Science, by definition, is limited to naturalistic methods and explanations and, as such, is precluded from using supernatural elements in the production of scientific knowledge' (quoted from Pennock 2011, p. 197). Scientific naturalism pervades the whole of science from A to Z. As such, it describes a core aspect of science that contributes to its unity.

A final virtue of the family resemblance approach is that it is free of philosophical commitments such as realism, positivism, empiricism and constructivism. One can adopt any one of these, depending on how one wants to spell out each item that falls under each category of the family resemblance approach. For example, while realist educators may wish to emphasise truth as an aim of science with respect to both observable and unobservable entities, those who are sympathetic to constructivism may settle for viability, provided that they inform students of the existence of alternative views on this issue. Thus, they can add content to the family resemblance approach according to their philosophical orientation or else completely avoid discussing these philosophical issues due to the pressure of limited time, the level of the class and so on.

30.7 Teaching the Family Resemblance Approach: Some Suggestions

Teaching NOS from the perspective of family resemblance can begin by introducing the categories of science and then showing how they are related to one another. A natural place to start is processes of inquiry since all students are engaged in them to varying degrees. A host of interesting questions can be pursued in this context. Is observing a passive activity (raised to illustrate the point that data collection is often driven by scientific problems and theories)? How does observation differ from experimentation? What are the different ways in which a given set of data be interpreted? And so on. Next, the teacher can explore the connection between processes of inquiry, aims and hypotheses (or models and theories). This could be motivated very naturally since processes of inquiry are activities and virtually all activities have some aim or other. Some of the questions that can be asked are as follows. What is the point of doing an experiment? How are observational and experimental data related to hypotheses, theories and models? Does this theory explain that set of data? How would an experiment be set up to test some claim? These and similar questions enable the teacher to make several points: data provide evidence for or against hypotheses, theories and models; experiments are conducted to test them; testing can be done (as in the hypothetico-deductive method) by deducing test predictions from them. The aforementioned questions also provide excellent opportunities for the teacher to discuss key scientific notions like 'testing', 'experiment', 'theory', 'law' and 'model'.

Another fruitful question that prompts the exploration of the relationships amongst various science categories is to ask how science achieves its aims. This may lead to the idea of scientific method and methodological rule. In this context, at least three points can be made. First, science does not achieve its various aims haphazardly, but by employing a number of methods and methodological rules. With their help, science produces reliable (though fallible) knowledge. The hypothetico-deductive method, in particular, enables students to see this clearly. Scientific predictions do not always come out right, and when that is the case, it means that scientists have made a mistake somewhere and they must revise some of their claims. In this way, science can eliminate its errors and produce more reliable results.

Second, methods and methodological rules do not dictate to scientists what to do at every step of their inquiry. A discussion of this point may help students appreciate the fact that scientific methods and rules are not mechanical procedures that generate theories (or models) from data. Hence, theory construction always requires much imagination and creativity. To stimulate creativity, students may be invited to come up with different hypotheses that fit or explain the same data.

Third, despite the existence of methods, methodological rules and values functioning as criteria for evaluating rival theories, scientists may sometimes come to reach different conclusions on the basis of the same body of evidence. This may happen when no single theory embodies all the cognitive-epistemic values equally well and when different scientists place different emphasis on them when faced with a choice amongst rival theories. One scientist may give more weight to fruitfulness, say, and another may value simplicity more due to the priority given to aesthetic considerations (in which case there will be disagreement about which theory is the better one). A historical example that comes close to this scenario is the debate scientists had between Aristotelian-Ptolemaic geocentric system and the Copernican heliocentric system during the early stages of the scientific revolution. The teacher may discuss this case as example of *rational disagreement* amongst scientists, a disagreement which in no way implies that they are acting arbitrarily, though they might have subjective (personal) preferences in weighing values. Properly understood, then, being subjective does not mean acting arbitrarily, which is the whole point of Kuhn (1977). In this way, students can see how both personal (subjective) and intersubjective (objective) factors play a role in scientific theory choice.

Once the students grasp the categories 'processes of inquiry', 'aims and values' and 'methods and methodological rules', then the fourth category can be introduced in a straightforward way: scientific knowledge, especially in the form of theories and models, is the end product of successful scientific inquiry pursuing the aims of truth, testability, prediction and the like under the guidance of scientific methods and methodological rules. The teacher can then draw attention to and explain the characteristics of scientific knowledge which have emerged (such as its empirical, objective and subjective nature, its reliability or tentativeness, its dependence on creativity).

As for the teaching of science as a social-institutional system, we foreground two categories: the scientific ethos and the social certification of scientific knowledge. What must be especially emphasised with respect to these categories is their function in scientific knowledge production. Students must understand that ethical norms like intellectual honesty and openness and social mechanisms of peer review and free and critical discussion are as important as processes of inquiry such as experimenting or in using methods, like the hypothetico-deductive method of testing, in producing *reliable* knowledge. This point can be made forcefully by inviting students to think about what happens if scientists were to fabricate data or to accept an idea or a theory without sufficient critical discussion.

30.8 Conclusion

The main point of this chapter is to suggest a new way of understanding the term 'nature' as it gets employed in the phrase 'nature of science' (NOS). The word 'science' is a broad umbrella term which, in the context of science education, cannot be unproblematically captured by proposing accounts of 'nature' which are essentialist or by specifying a set of necessary and sufficient conditions for science. Nor can it be captured by drawing up some small list of features. The problem with a list is that it remains arbitrary as to why some features are included on the list and not others; and it remains unclear how, when given such a list, one is to go on to features not mentioned on the list. Our answer is to suggest the family resemblance or cluster account of a definition—an account developed within philosophy to overcome problems with essentialism, necessary and sufficient conditions and lists already mentioned. As such our enterprise is more philosophical and is not directed upon empirical matters such as the kinds of understanding teachers and pupils might have of NOS, or what level matters pertaining to NOS might be discussed in classrooms. Nevertheless, the family resemblance conception of 'nature' that we have proposed is not irrelevant to these empirical matters. What it does is 'free up' one's approach to them in what we hope is an illuminating way which a too rigid conception of 'nature' might obscure.

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