Scientific Knowledge

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Definition

Scientific knowledge has gained renewed attention in the so-called knowledge-based society today. Challenges and crises highlight the question of what scientific knowledge is and what science can achieve. Especially in inter- and transdisciplinary contexts, one should be aware of the potential of scientific knowledge, but also of the reductionism inherent in a scientific approach.

Defining what scientific knowledge is, what it means when someone claims to know something based on evidence and what this knowledge implies, is part of scientific and philosophical reflections. These questions that originated in ancient Greece were discussed by numerous philosophers, such as Aristotle, Bacon, or Popper, thereby developing the rules of what is today accepted and applied as a scientific approach. Therefore, knowledge acquired via adhering to these rules must be accepted as scientific knowledge (Kuhn and Vessuri 2016, 11).

The term *scientific knowledge* has, regarding its etymology, a double name. *Knowledge* is an Old English word describing the fact of being acquainted with a thing or a familiarity gained by experience (Oxford University Press 2022a). The attribution *scientific* relates to the Latin *scient-, sciēns*, present participle of *scīre*, which means "to know", so knowledge as opposed to belief (Oxford University Press 2022b).

Scientific knowledge is gained via a specific process which adheres to the conditions of science, here used in the embracing notion including non-empirical sciences such as mathematics, law, philosophy, linguistics, and history. The UNESCO (2018, 5) defines science as the

> enterprise whereby humankind, acting individually or in small or large groups, makes an organized attempt, by means of the objective study of observed phenomena and its validation through sharing of findings and data and through peer review, to discover and master the chain of causalities, relations or interaction; brings together in a coordinated form subsystems of knowledge by means of sys-

> tematic reflection and conceptualization; and thereby furnishes itself with the opportunity of using, to its own advantage, understanding of the processes and phenomena occurring in nature and society.

There is no final definition of scientific knowledge, the term is still frequently discussed within and between different scientific disciplines. It encompasses empirical, theoretical, and hermeneutical approaches towards a systematic knowledge acquisition. However, researchers and students should be aware of the various conceptions of knowledge implied in different scholarly cultures. Within transdisciplinary learning contexts, the different cultures of knowledge provide the potential for a more holistic reflection, and therefore more comprehensive understanding. Persons who intend to collaborate in a transdisciplinary research project or educational task should reflect on and communicate their sources of knowledge, its reliability, and limitations. Conscious discussion may enhance mutual understanding for different approaches, documentation, and methodologies in scientific knowledge acquisition and therefore may prevent possible misconceptions (Pohl et al. 2021, 18–19). In addition, this reflection may help to identify common points of contact and complementary additions to the various disciplinary levels of knowledge, thereby enhancing mutual learning.

Background

The conception of scientific knowledge and how scientists gain knowledge is part of epistemology. Epistemology deals with the origin, nature, and limits of human knowledge (Stroll and Martinich 2022). Philosophers, historians, and science sociologists contribute to the subject. The modern scientific system can be divided into three areas.

First, science as a *system of knowledge*. Scientists use terms to specify the origin, conditions, and reliability of statements. They differ between hypotheses – tentative explanations that need to be tested by further investigation; scientific laws – statements that describe the relationship between certain variables under given conditions; and theories – well-substantiated, overarching explanations of natural phenomena. Further, scientific knowledge is classified using disciplinary typologies, grouping items or concepts based on commonalities they share, like the taxonomy in biological classification. These typologies are developed by scholars forming a thought collective (Fleck 1979, 99), which means that they share a framework of ideas, cultural customs, and experiential knowledge.

Second, science as an *organized process*. In their research, scholars apply different methodological approaches including empiricism, analytical methods, and hermeneutics. Empiricism involves careful observation, applying rigorous skepticism about interpretation of observations. It involves formulating hypotheses via induction, experimental testing of deductions and refinement (or elimination) of the hypotheses based on the experimental findings. Not all steps take place in every procedure to the same degree and in the same order. Researchers use analytical methods to reveal type, structure, and function of an object by breaking it down into its components and describing their relationships on a theoretical basis. Hermeneutics describe the theory and practice of interpretation. It reflects the nature, scope, and validity of statements, for example, inherent in texts or observations. Thereby, it can help an understanding of how problems are defined and situate them in a societal and historical context.

Third, science as *cultural achievement*. Scientific knowledge is organized in institutions with specific rules and values, and with a societal role and responsibility. For Europe, this culture has its origins in ancient Greece and, through knowledge exchanges, such as e.g. with the Arab world, has developed over the centuries into modern science as we experience it today. Science in the scholarly sense described above is today applied universally.

The history of scientific knowledge is complex, and a multitude of perspectives and notions exist. However, it is possible to highlight key developments that have led to the emergence of the modern science system. The Greco-Roman ancient world represents a distinct cultural area that produced significant scientific advances and is today regarded as the cultural origin of European science traditions. The first period of scientific history in ancient Greece was characterized by developments in research methods, the formation of rules and systematization, the observation of the course of diseases or the study of order in nature (Merlin 2014, 16–21). Natural philosophers from this period, like Socrates, Plato, or Aristotle, engaged in the earliest known forms of what is today recognized as rational scientific knowledge acquisition. Aristotle's inductive-deductive method used a cyclic process of inductions from observations to infer general principles and deductions from those principles to check against further observations to continue the advance of knowledge systems. Based on Aristotle's work, in the Middle Ages the scientific systematics of scholasticism were developed including, for example, the work of Thomas Aquinas and William of Ockham, elaborating the proof of evidence via disputation (Marrone 2006, 32–37). Assertions were developed based on assumptions, which were then tested for arguments for and against this assertion with the help of logical considerations.

However, during the 16th century English humanists began to value practical knowledge more than solely theoretical consideration, thereby rejecting scholastic disputation (Gaukroger 2001, 6–15). The pursuit of practical knowledge was one major aim Bacon followed (Gaukroger 2001, 9–10, 101). With the help of his commitment to observation and experiment, empiricism became a central part in the reform of natural philosophy towards modern science. This era of scientific revolution achieved "facts, principles, laws, hypotheses, and theories [being] subject to objective judgment in the light of empirical evidence" (Wenning 2009, 12). Furthermore, humanists, such as Nicholas of Cusa and Bacon, recognized the unique role of the researcher, which was a remarkable step in raising awareness of the cultural dimension within science and scientific knowledge. Bacon proposed rules of conduct for researchers, claiming the requisite of good sense and behavior in observation and experiment (Bacon 1620; Gaukroger 2001, 12). With his publication *Discourse on the Method,* Descartes is also recognized as pioneer of the development of modern natural science, especially for emphasizing the significance of doubt or skepticism as an essential attitude for scientific reasoning (Descartes 1637, part two).

In the 17th and 18th centuries, the development of more formalized processes of knowledge creation through empiricism or mathematical reconstruction led to an enormous increase in scientific data that had to be collected and ordered. The amount of available information increased the pressure to treat data selectively, depending on scientific criteria. Furthermore, experimental settings allowed scholars to construct their research around specific subjects and phenomena. Scholars communicated concepts and methods that were more specific to these subjects, finally leading to specialized journals and communities. Through this specialization, the disciplines in the modern sense emerged around 1800. They became institutionalized in scholarly associations and universities. This further structured knowledge formation and conception, its distribution in research and teaching, and its application. The enormous growth of science stimulated by the disciplinary development forced the system to further structuring and internal differentiation, and, therefore, to a multiplication of disciplines. Scholars had to focus their attention on a specific field, thereby leading to an increase in specialization. Although the loss of scientific unity was perceived by scholars themselves, it was not until around 1970 that public attention to environmental protection and technological developments fueled the debate on inter- and transdisciplinarity (Weingart 2010). The previous accumulation of knowledge and techniques within delimited disciplines now allows complex problems to be viewed from different perspectives.

Debate and criticism

The major challenges facing society today are characterized by a multi-layered nature and complex underlying causal chains. Their complexity does not allow for solutions developed within one discipline (Mittelstraß 1987, 154–55), despite the profound stock of disciplinary knowledge available. Researchers need to unify different knowledge perspectives in order to address these challenges in a transformative manner. While the natural sciences can provide insights into laws and relationships, the humanities can offer reflective perspectives and elucidate the cultural embeddedness of observations. Transdisciplinary research thereby represents a complement to disciplinary research, not a replacement. It builds on multidisciplinary research, so addressing the same problem within different disciplines, and by final sharing of results, it combines findings within a common context. It also builds on interdisciplinary research, which means a close interaction between different disciplines in terms of transferring methods and knowledge at an early stage, as well as close cooperation throughout the research process. Furthermore, transdisciplinary approaches also often involve societal actors to integrate their knowledge and perspective (Lawrence et al. 2022, 44–48). A successful integration of these different types of knowledge and practices in such collaborative processes can lead to mutual learning, a more holistic perception of issues, and synergistic, innovative approaches in searching for solutions to societal problems. This integration can only be achieved when the scientists themselves become aware of the properties of disciplinary knowledge, the processes of its development, and its boundaries. Higher education should therefore help to reflect the relevance of mono-, multi-, inter-, and transdisciplinarity to complex problems. Teachers and students should become aware that many disciplinary perspectives exist and that they are not static, but are evolving based on progress in their own as well as in other disciplines (Vereijken et al. 2022, 6). The comprehension of basic scientific concepts and a solid understanding of the epistemological characteristics that are part of disciplinary knowledge are essential baselines for transdisciplinary problem-solving. Here, the concept of Nature of Science could serve as an example for educational implementation.

Nature of Science encompasses an understanding of the epistemic, historical, social, and cultural reach of scientific knowledge as well as an understanding of scientific reasoning and methods. It further reflects the values and norms to justify scientific claims (Heering and Kremer 2018). Since the 1960s, Nature of Science was increasingly taken up by science educators and was then central in the debate from the 1990s (Heering and Kremer 2018, 105; Lederman et al. 2002, 498). Communicating the overarching ideas in science that hold true in several disciplines are today seen as superior outcomes for science education (Lederman et al. 2013, 138–39). One educational aim within Nature of Science is to convey that “scientific knowledge is tentative, empirical, theory-laden, partly the product of human inference, imagination and creativity, and socially and culturally embedded” (Lederman et al. 2002, 499). The authors furthermore underline the importance of teaching the distinction between observation and inference, the lack of a universal method within science, and the functions and relationships between theories and laws in science. Scholars from different disciplines, however, still controversially discuss conceptions of Nature of Science.

Today, educators all over the world accept the comprehensive understanding of Nature of Science as a goal to be achieved in the science classroom and informal educational settings (Allchin 2011, 519; Lederman et al. 2013, 138). Several studies investigated how the explicit reflection of Nature of Science during education supported its understanding, whereby longitudinal studies showed only short-term gains (summarized in Cullinane and Erduran 2022, 2). Alternatives to the rather general "consensus view" of Nature of Science (Lederman et al. 2013, 138) were discussed. Allchin's (2011) "Whole Science" framework highlights dimensions that shape the reliability of science, so that students are empowered for personal and public decision-making. Erduran and Dragher (2014) presented their "Family Resemblance Approach" that provides perspectives on similarities and unique differences of the discipline-specific Nature of Science, such as for chemistry, physics, and biology.

Considering not only the potential but also the limits of scientific knowledge, helps us realize the significance of the plurality of knowledge sources and to recognize other types of knowledge, like indigenous or practitioners' knowledge (Tengö et al. 2014, 579). Indigenous knowledge refers to knowledge with different forms of legitimation and tradition, e.g. through generations of naturalistic observation, place- and community-based insight. From the 1990s onwards, members of the research community have called for the recognition of other cultures of knowledge besides the "Standard Account". This considers knowledge as scientific in the sense of Western culture based on ancient Greek and European heritage (Cobern and Loving 2001, 52–56). As summarized by Cobern and Loving (2001, 54), movements such as multiculturalism (Stanley and Brickhouse 1994), post-colonialism (Rigney 2001), and post-modernism (Lyotard et al. 1995) enabled new epistemological perspectives on the relationship between science, culture, and the 'Standard Account' itself. The conception of scientific knowledge in the standard account helps us to perceive its inherent nature, since it is clearly defined within its disciplinary boundaries and is integrated into educational systems all over the globe. This helps us to place and relate scientific knowledge worldwide in a similar manner, with all the constraints mentioned above. The perception of other knowledge forms, e.g. indigenous knowledge, may be limited due to different cultural backgrounds (Sidik 2022). It is essential to recognize the value and the potential inherent in the diversity of different knowledge forms for more holistic approaches, better ways of social inclusion and their huge potential to support societal transformation. The integration of diverse knowledge systems in transdisciplinary education and research can be challenging (Tengö et al. 2014, 581–82). Therefore, Nature of Science could function as an informative guide for the integration of other knowledge forms. The communication and discussion of their nature in transdisciplinary projects may help to integrate them in a respectful, valid, and synergistic manner.

Current forms of implementation in higher education

In modern science education, the understanding of Nature of Science is a critical component (Khishfe 2022). Therefore, three basic approaches to Nature of Science contextualization are proposed and can be adopted for higher education. Understanding the Nature of Science can be promoted (1) through the integration of case studies from the history and philosophy of science, (2) through the consideration of the mutual influence of science, technology, and society using contemporary cases, as well as (3) through the reflection of individual experimental-research activities using inquiry-based cases (Allchin et al. 2014; Kremer 2008).

The history of science can provide effective Nature of Science contexts. It allows the scientific process and the tentativeness of scientific knowledge to be addressed. It provides insight into the subjective and cultural dimension of science. Another advantage is that the case is already completed in time and thus can help in understanding the evolution of scientific knowledge and the interplay with society. For example, Paraskevopoulou and Koliopoulos (2011, 943) developed a teaching intervention about the dispute between Millikan and Ehrenhaft about the existence of the elementary electrical charge. Douglas Allchin (2012) provides a collection of historical cases for the reflection of Nature of Science and the interplay between science and social and political circumstances.

Using contemporary cases that show the relationship between science and society offer insights into open and controversial debates. Science education researchers contextualized Nature of Science using current socio-scientific issues (Khishfe 2022). For example, press articles or interviews with scientists on the Covid-19 pandemic can serve as material for discussion. In order to be able to bridge the holistic, people-oriented, contextual, social, and personal life-world image and the analytical and objective scientific image that are both part of socio-scientific issues, Zeyer (2022, 5–6) proposes a "Two-Eyed Seeing" method for science teaching. By switching between the two images which can stand side by side, this stereoscopic view provides a more encompassing picture of the world.

The contextualization using inquiry-based cases builds on the conception that Nature of Science can be better understood by actively constructing such knowledge. When the learners engage in a scientific inquiry and reflect on this process, they may gain insight in the nature of the scientific process. Science communication research shows that citizen science has the potential to improve Nature of Science knowledge and attitudes as well as inquiry skills among participants (Peter et al. 2021). Thus, the design and participation in citizen science settings is another promising scenario for transdisciplinarity in higher education.

Teaching scientific knowledge in transdisciplinary contexts in higher education needs both – teaching discipline-specific concepts and knowledge, and teaching ways to transcend disciplinary boundaries to connect complementary fields. In this sense, Baumber et al. (2020, 396) provide a case study focusing on the development and implementation of a four-year curriculum for the Bachelor of Creative Intelligence and Innovation at the University of Technology Sidney. Students first follow three years of disciplinary education and then accomplish a joint fourth year. The curriculum employs a transdisciplinary learning approach based on addressing complex real-world challenges through collaboration and mutual learning across disciplines and with a variety of industry, government, and community partners.

The contextualized reflection of the role of scientific knowledge in historical and contemporary research cases as well as during personal inquiry experiences provides an inevitable foundation for transdisciplinary knowledge formation processes in higher education settings, as it can clarify the contributions, the limitations, as well as the social and political embeddedness of different disciplines.

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