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DISCUSSION PAPER

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This discussion paper was commissioned by the ISC to provoke discussion and reflection. As such, it should be seen as the opinions of the authors.

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INTRODUCTION: SCIENCE IN CONTEMPORARY CONTEXT

In the following we use the term 'science' in a broader sense than the usual English meaning. Our interpretation is closer to the German term 'Wissenschaft', which includes scholarship from the social sciences, humanities and jurisprudence.

Science is undoubtedly one of the main drivers of human development and technology. The recent rapid development of vaccines to address COVID-19 is widely recognized as a triumph of science. Science is also a major input to our understanding of the world around us, even when this world is complex, as for instance the global shifts due to climate change. Biological sciences give us knowledge about ecosystems and the threat of reduced biodiversity. Social sciences provide us with insights into the human condition, trends in political opinions and drivers for refugee movements. Religious studies illustrate differences and similarities between the world's great religions, while historians produce insights and lively narratives of cultures of our past. Obviously, this is just a small selection of the value the public receives from science, many more examples could be added.

Yet, to see the whole picture, we must acknowledge the double-sidedness of contemporary science and the apparent ambiguity surrounding the value of the scientific knowledge we currently produce in such abundance. We must step outside the scientific community to understand attitudes to science across large segments of diverse publics. Present-day science is not shielded from substantial criticism and mistrust.

Some of this criticism is rooted in the undeniable fact that many problems we face today are the result of the application of past developments in science and technology. Innovations to solve one problem have created other and new problems as the result of their unintended consequences (Gluckman and Hanson, 2019; Leach, 2020). The Green Revolution is a good example of this. We improved the productivity of our food production systems, only to realize that we had unintentionally created a wealth of environmental problems. When we put science into action to solve one problem, we created the problems of the next generation.

Consider another pressing problem today: climate change. We now agree that climate change occurs and that the major driver for the temperature increase is human activity which, in turn, is largely driven by technological developments arising in the nineteenth century and leading to a carbon-based global economy. At the same time, we now recognize the inherent complexity of the grand societal challenges we are facing, not only climate change, but the health of humans, animals, and the environment. To these we can add the digitization of society, ageing populations, social cohesion, depletion of natural resources, food systems and food security, water scarcity, urbanization, economic volatility and global inequities (The Global North versus The Global South, gender, race, etc.). We have come to realize that these issues are inherently *complex* (not just complicated). They require careful consideration of scale and scope, are cross-disciplinary, defy precise predictions because of non-linearity and are interdependent in that they interact and impact each other. They are essentially what have been termed '*wicked problems*' (Rittel and Webber, 1973). In the face of these challenges, it is small wonder that some people doubt the potential of science to help us. A general trust in science to solve our problems seems a phenomenon of the past.

Finally, on the ideological front, there are extreme political variants of post-modernism, resulting in what the media have termed a 'post-truth' society, liberally scattered with 'alternative facts', hate-induced racism and conspiracy theories. Disinformation in its various forms is a worrying trend, especially because we often do not know how to effectively counter it. This trend is broadly anti-science and undermines public trust in science.

As a consequence, present-day science needs to reflect on its own practices and consider how some of them could be adapted to meet the highly complex grand societal challenges and to improve its public acceptance. Science needs to find and try new forms of research and partnership to ensure public trust, and to be a reliable input into societal decision-making and policy-making, while also continuing with traditional modes of enquiry.

We believe it is time for reflection, for science and for societies in general. As scientists, we need to examine our practice, get to the roots of our activity (research) and the institutions through which science operates (the science system). We must ask how science and science systems can improve or evolve to become a trusted partner in the global societal and environmental changes that must be set in motion. In terms of substance for this reflectivity, we will address what may sound like simple questions, but which, on inspection, lead us to deeply philosophical if not ideological disputes. The apparently simple questions are: (a) What is science? (b) What is the relationship between science and action? (c) What are inter- and transdisciplinarity? (d) How do science and transdisciplinarity relate to other knowledge systems? (e) How can we improve the science–society and science-for-policy interfaces?

OVERVIEW OF THE MAIN POINTS IN THE PAPER

Let us sketch our answers to the above questions as a hopefully useful guide to this discussion paper, which is intended to promote discourse and reflection:

a) The drive to understand the world around and within us and to obtain knowledge about it has been a defining feature of human existence since the dawn of humanity. This desire has been culturally addressed in various ways. While it has earlier origins, in the last 500 years, different knowledge traditions culminated in the rise of what we now recognize as the sources, principles and characteristics of modern science. We see the combination of methodological and epistemological constraints on ways to obtain knowledge about the world and socially organized forms of practice to produce, communicate and validate claims of knowledge as crucial elements of the core of modern science. Though these principles may have been most condensed and influential in the Western world of the late Renaissance (with the rise of new scientific academies), several of the core ideas were foreshadowed earlier in other cultures. Part of the aspirations of the principles were that they be universal. We contrast the *principles* of modern science, which are universal, to the *systems of science*, as they were institutionalized later, particularly since the early nineteenth century. The latter show diversity and the impact of context and history. New universities and institutes became essential parts of the institutional settings of modern science and expressed a system of science that reflected ideology and power structures of the dominant Western culture. The emergent division into separate academic disciplines became part of the training and practice of science. We claim that it is important to distinguish the (ideal) principles of science from the systems of science, which to a significant extent embody and reflect the socio-political conditions of the institutionalization of science in different parts of the world.

b) This paper describes how the potential of scientific knowledge to lead to socio-technological change has been realized since the Scientific Revolution and intensified with the Industrial Revolution. Industrialized science is responsible for many technological innovations which have changed people's lives. It was also an important contributor to weaponry in two World Wars, thus adding to an ambiguity in peoples' beliefs about the benefits of scientific progress. After World War II and the state entering as both a big funder and driver of scientific research, the need to counterbalance the innovative forces of science with external controls of the associated risks emerged. With studies emerging in areas such as risk assessment, technology assessment and system analysis, the realization gradually emerged that the apparatus and models of scientific disciplines were not sufficient to deal with many issues in a comprehensive manner. Many scientists saw their roles extended beyond their traditional roles. They became promoters and advisors of socio-technological change, sometimes the critics, whistleblowers or political opponents of such change, and sometimes the regulators or communicators of the embedding of techno-scientific innovations in society. With this development came the realization that products of science always interact with other factors in a complex social reality. Consequently, the role of scientists in this complex web of interactions became as multi-faceted as the products itself.

c) The realization came slowly that purely disciplinary knowledge seldom addresses issues which are inherently complex and require the linking of many systems differing in scale and scope. Nor can it provide the essential societal impetus for change that often is both costly, uncertain in outcome and disputed by different interests. The move to interdisciplinarity was mainly motivated by the wish to cross disciplinary boundaries and public participation a means to identify the areas of relevant expertise. Transdisciplinarity goes beyond this effort in attempting to realize more demanding goals. It involves opening up to include knowledge and areas of expertise outside the academic fields. It combines more holistic knowledge generation with empowerment for those who are affected by an issue and can change it. It considers constraining interests and bias through inbuilt reflexivity. It better understands underlying value-based dynamics, and it ensures ways out of a problematic issue are socially robust and socio-politically realistic. While transdisciplinarity does not imply an overarching unified method or novel theory of knowledge, it can be characterized by its more general normative aspirations, which still allow for a variety of concrete project designs adjusted to specific contexts. In this sense, transdisciplinarity is here presented as a general framework, rather than a specific method.

d) The underlying philosophy of the paper is that the quality of all knowledge claims effectively hinges on the question of whether the knowledge is fit-for-purpose. Given that we seek out knowledge for a variety of purposes, the characteristics of the knowledge will typically also vary. While our sciences serve a number of these purposes, the realities of human existence and social interactions provide a richer framework of contextually constrained purposes which science can often only partially address. The view presented in the paper stresses the important role of professional or experiential expertise and particularly recognizes the role of Indigenous knowledge systems. Recognizing and respecting these different knowledge systems is not merely an ethical issue but is here presented as the consequence of the complexity of the issues and the need to be sophisticated in our honest attempts to improve the *status quo*. In the view of the authors, this does not diminish the relatively important and somewhat privileged role of science as an advisor to policy and a trusted partner of the public. For science, when realized according to its principles, aspires to a system of self-correcting assertions free of religious beliefs or other ideological worldviews which are not subject to the test of empirical realities.

e) The goal of transdisciplinary research is recognized as a challenging objective that does not easily fit into today's' funding mechanisms or dominant quality assessments. Major institutional changes will be required to provide conditions for a wider and appropriate use of transdisciplinary research designs. Since context is an important feature in all transdisciplinary research, quality assessments and funding must be responsive to the specific, often local, conditions of the research. Traditional measures of scientific quality and outcomes must be transcended. Different phases of the research, such as shaping, supporting and evaluating (Carew and Wickson, 2010) must be accompanied by new criteria of assessment and promotion. Furthermore, institutional change may also require more flexible funding mechanisms and collaboration across institutions and nations. These changes should add to rather than replace existing funding mechanisms of disciplinary science.

In the remainder of this paper, we attempt to detail these answers, answers that admittedly will remain incomplete, but which could muster some wider consensus as they describe the core of our activities and profession. Our answers are structured in three parts: Part 1: What is science?; Part 2: The road to transdisciplinarity; Part 3: Making transdisciplinarity real.

PART 1: WHAT IS SCIENCE?

THE QUEST FOR KNOWLEDGE

Through biological evolution, humans have acquired the capacity to cumulatively learn across generations, to store knowledge collectively (through stories, song, art, writing, etc.), and to improve their manipulative skills allowing for cultural change. Aristotle wrote 'All men by nature desire to know' (Aristotle, *Metaphysics*) and this is the inevitable outcome of our evolved capacities. We find the quest for knowledge in all instances and stages of human culture and society. However, our cultural evolution also has other consequences. It has allowed us to manipulate and alter our environment beyond simply the need to sustain Darwinian fitness, that is, the capacity to reproduce successfully and sustain a lineage. Rather, much of our progressive manipulation of our physical, technological and cultural environment has been for other purposes; for example, for economic or hedonistic value (Low et al., 2019). But, irrespective of whether they are part of ancient or modern society, humans have a need to understand the processes around them. In other words, humans need to develop some workable knowledge of their environment. They need to provide meaning and explanation to what they observe.

Two general observations are in order here. First, until recently, the knowledge that was sought was largely linked to a *locality*. That is, it involved those entities that the specific populations encountered; however, this does not imply that the knowledge could not be transferred to other localities. Second, knowledge about the concrete can be cast and embedded in concepts and frameworks which are *beyond* concrete experiences. Mythology, religion, magic, as well as natural causes were often the framework within which this knowledge was cast and developed. Even though modern scientists tend to draw strict boundaries in relation to religion and mythology, historically, these boundaries were mostly 'blurry' for a long time. Even 'Western' conceptual differentiation between *knowledge* and *belief* is blurry, and these terms do not always translate easily.

Knowledge guided the relationships among humans in their small-scale societies, their relationships to the non-human animal world and their relationships to their natural environment in general. Indigenous knowledge systems contributed to utilize, master and shape the landscape of those cultures. Knowledge was also often tied to specific skills (like fishing and navigating) and could result in special tools to manage the environment (from stone axes onwards).

One important element in all of science is the ability to observe and represent your environment correctly. We have evidence of very early cave paintings made by Neanderthals (c. 65 thousand years ago), and we have cave paintings and artistic objects made by early humans (c. 40 thousand years ago). Often, they depict aspects of the natural world in astounding detail.

Humans not only observe their environment, but they also tried to understand it and find answers to their why-questions. For this, they broke through the surface of the observable phenomena and looked for underlying structures that could explain them. They typically found in mythical or religious beliefs, built on powers beyond our direct experience. These were 'deep' explanations (cf. Strevens, 2020). Even modern science seeks for the underlying structures to any observation, but instead of resorting to supernatural powers, it seeks causes based on logic, observation and reality ('shallow' explanations).

One of the main lessons from the study of ancient and Indigenous cultures over millennia to the present day is that contributions to knowledge come from many varied sources and they have been expressed through various media. Oral traditions led to a certain fluidity of knowledge which was adapted to new needs and circumstances, and carried with the tribes when they moved to new locations.

Figure 1. Little wild horse carving in mammoth ivory, c. 40 thousand years old; Tübingen University Museum.

Source: https://commons.wikimedia.org/wiki/File:MUT-9846.jpg

After 'prehistoric' times, the emergence of the great ancient cultures meant significant 'progress' in the knowledge that was produced, progress at least in the sense that the knowledge was in some sense more 'portable' and could lead to more useful technologies. The early Mesopotamians had impressive chemical knowledge of clay and other materials, which gave them the technology for pottery. Geometry in ancient Egypt was a tool to measure and reinstate land property after floodings of the Nile. Sometime between the first and fourth century, the Hindu–Arabic numeral system was introduced, including the base of zero. It travelled and was much later introduced in Europe via the Mesopotamic and especially the Islamic world. The influence of the Islamic world on the eventual growth of mathematical knowledge can hardly be overstated: algebra, trigonometry and mathematical improvements of (geocentric) astronomy were some of the contributions that set the scene for modern mathematics.

Of course, there are many more examples of knowledge generation from different places and cultures with different subjects (Needham, 1954) (Zhang, 2022). [1] To mention another one: health and medicine were largely promoted by the uptake of Hellenic medical writing (Galen) into the Islamic world, and later by writers such as Ibn Sina (Avicenna) who, among others, discovered the contagious nature of infectious diseases. Hospitals as institutions for the sick came largely from the Islamic world.

Classical antiquity in Europe was indebted to influences from other cultures but also contributed to them. Thinkers like Aristotle were not only writing about what we now term philosophy or ethics but contributed to a wide field of knowledge. On Lesvos, with Theophrastos, he developed biological knowledge about many amphibious organisms, largely derived from vivisection. Many of his findings are still valid today. Yet, when looking at this knowledge from the perspective of a modern biologist, one also sees that Aristotle had not yet embraced what we now call the scientific method or at least a major part of it: the critical testing of a hypothesis was not even considered.

There were institutions for learning like the madrasas in the Islamic world in the Middle Ages, the Al-Azhar University in Cairo (founded c. AD 970), and the universities of Europe which came out of monasteries. The first European one was founded in Bologna in AD 1088. The European Middle Ages saw an increase in influences from other cultures (partly due to Pax Mongolica). These spread rapidly through the invention of the printing press. However, they also allowed the fixation of knowledge to sources of classical antiquity.

1 One question that was – and to some extent still is – intensively discussed among historians of science is whether ancient China displayed an advanced but culturally different form of early science, or whether China was highly advanced in technology but not in science. This was the leading question that Joseph Needham asked in his famous book series Science and Civilization in China. As Zhang (2022) observes, using the definition and classification system of modern science to look for its roots in ancient China amounts to what is called a 'Whiggish history', a history written with the hindsight of present-day Western culture. Evaluating the significance of the (Chinese) ancient cultural contributions to science and knowledge from such a vantage point will introduce biases of understanding which studies in cultural history try hard to avoid.

Were these early knowledge traditions, these forerunners of what we now call science, doing science as we understand it? In the sense that knowledge of the natural world is an essential part of all our modern science, these knowledge traditions were obviously developing something that did feed into scientific development. On the other hand, the development of hypotheses to be tested against experience, the willingness to stick to a paucity of explanatory factors of natural phenomena that were absolutely necessary, and the recognition of the important critical role of the community of scholars are largely absent in these traditions. There are, however, glimpses of what was to follow – for example in the propositions of Arabian scholars such as Ibn al-Haytham (AD 965–1040), which were very similar in nature to those that were to emerge later in Europe.[2] Forerunners such as Ibn al-Haytham show how the human mind gradually discovered the strength of the concepts and principles of critical knowledge development. But science as we now generally understand it only changed during the Renaissance, during what we now call the Scientific Revolution (1550–1750).

THE EMERGENCE OF THE PRINCIPLES OF MODERN SCIENCE

The term 'science' derives from the Latin, 'scientia', a translation of the Greek word 'episteme', depicting knowledge as opposed to 'doxa' (opinion, beliefs). However, its original meaning was based on knowledge acquired in the Aristotelian sense, based on syllogisms and observation. The term has changed meaning over the centuries. In the late Middle Ages, it entered the English language from French, but was still not understood as in the modern scientific way of studying reality. The Scientific Revolution used the term 'natural philosophy' ('philosophia naturalis') when the new way of study and research was introduced. It was only at the beginning of nineteenth century that the modern use was introduced marking the transition from the amateur natural philosopher of the Scientific Revolution to the professional scientist. The philosopher and polymath William Whewell wrote in 1840: 'We need very much a name to describe a cultivator of science in general. I should incline to call him a Scientist.'

Modern science wherever it is practiced comes with a history, and that history has its main roots in the Scientific Revolution (c. 1550–1750).[3] The Renaissance re-discovered some of the classic arts, most importantly the power of mathematics. It was Galileo Galilei who first stated that the laws of nature are cast in the form of mathematics. Nature became quantified and measurable. This also gave a new role to experiments, now conceived as tests of knowledge claims (cf. the famous inclined plane experiment). Explanatory theories, depicting causal relations between phenomena, had to be founded on observable or empirical facts of nature. Francis Bacon warned

2 'The duty of the man who investigates the writings of scientists, if learning the truth is his goal, is to make himself an enemy of all that he reads, and ... attack it from every side. He should also suspect himself as he performs his critical examination of it, so that he may avoid falling into either prejudice or leniency' (Ibn al-Haytham, here cited after Wikipedia). Ibn al-Haytham (AD 965–1040), also referred to by his Latin name, Alhazen, was born in Asra, Iraq, but lived most of his adult life in Cairo. He is probably one of the first true scientists who expressed what during the Scientific Revolution and Renaissance became a core of the Principles of Science. He stated that hypotheses need to be supported by experiment or mathematical evidence. His biggest achievements were in optics where he not only introduced the first camera obscura outside of China but also performed experiments with lenses and mirrors, analyzing reflection and refraction, and showing that light travels in straight lines. What is remarkable and often overlooked by historians of science is his insistence on critical and controlled testing of his hypotheses. He also used mathematics to help explain his physics. Ibn al-Haytham's main work, the Book of Optics, was widely read in the Arab world, but after translation into Latin, it was also read by many European scientists such as Roger Bacon, Galileo Galilei and Rene Descartes.

3 The authors are aware that there are many histories of the Scientific Revolution and its role as the origin of modern science. We agree with Henry (2016), however, that sometimes it is useful to concentrate on the 'big picture' rather than 'highly specialized studies' in historiography.

of the unwanted intrusion of the 'Idols of the marketplace' (e.g. philosophical, or metaphysical beliefs not founded in material reality), and this was powerfully stressed by, among others, Isaac Newton.[4] The material world became subject to analysis and synthesis, opening the path for reductionism, as for example, the solar system based on the movements of its components (the sun and planets). Thus, the new so-called *natural philosophy* introduced the principles of the *scientific method* as something that is based on experiment, measurement, quantification, observation of significant facts and best explanation of the observed phenomenon (cf. Strevens 2020). Only explanations based on observation, reality, logic and the scrutiny of peers became acceptable and have evolved to become the core principles defining science. Specifically, appeal to higher powers, belief or tradition was excluded as the basis of explanation.

Based on these core methods and principles, science continued to evolve more refined methods in various new disciplines, statistics among them. However, the main thrust remains that more abstract theoretical claims must be justified by their links to empirical data. The latter are epistemically prior to theory, or in plain words: theoretical justification follows observation and testing. As philosophers have been quick to point out: this does not imply that theoretical constructs do not influence our interpretation or even perception of empirical phenomena (theory-laden observation) but ultimately the justification goes from data to theory.

The Scientific Revolution also introduced another crucial element of science: scientific research as structured and validated in a *socially organized system of the scientific community*. The motto of one of the oldest scientific academies, The Royal Society (for improving Natural Knowledge) founded in London in 1660, encapsulated the scientific method in its motto '*Nullius in verba*', translated as 'take nobody's word for it' and verify all statements by appealing to facts determined by experiment. This they aimed to achieve through the new academies that were founded in the seventeenth century. Validation of knowledge claims were conducted with two critical elements: (a) presentation and discussion of the studies for the members, that is peers of the academy and (b) through publication in the new scientific journals, the *Transactions of the Royal Society* being the first scientific journal. Noteworthy here was that this natural philosophy was cosmo-political, universal[5] and submitted to public knowledge.

Institutionalizing scientific endeavour had to be justified in the socio-political framework of the time. Robert Hooke wrote in the draft for the charter of the Royal Society:

> *The business and design of the Royal Society [is] to improve the knowledge of natural things, and all useful Arts, Manufactures, Mechanick practices, Engynes, and Inventions by Experiments, - (not meddling with Divinity, Metaphysics, Moralls, Politicks, Grammar, Rhetorick, or Logick).*

This resembles modern day talk about innovation. The wish to signal neutrality vis-à-vis the dominant powers of the time was prominent. Yet, we could argue that the largest influence this new science had for roughly the next 200 years was not new and useful technology, but the influence this thinking had on the Age of Enlightenment. In some sense, the Enlightenment – the Age of Reason – was a triumph of this rigorous scientific, philosophical and social discourse as it overcame outdated traditions, beliefs, institutions and power structures. It was also the rise of 'Modernity' with the ensuing division between those institutions that were to consider the facts of the world, the sciences, and those institutions that were to consider values and socio-political actions, the state.

4 Newton, admitting he was as yet unable to deduce the reasons for the properties of gravity from the phenomena: 'hypotheses non fingo'.

5 See, for example, the subtitle of the first issue of the Transactions: 'Philosophical Transactions giving some Accompt of the present undertakings, studies, and labours of the Ingenious in many considerable parts of the World'.

What we find in this period is the consolidation of the 'Principles of Modern Science'. It was promoted by 'amateurs', people who did not usually pursue scientific research professionally but had either independent income or were employed by a sponsor in another capacity. Separate scientific disciplines had not yet emerged,[6] as the research went under the name of 'natural philosophy'. And – apart from the emerging academies – no professional organizations pursued scientific research according to these principles. Lorraine Daston (1991) sees this quest for impartiality, the critical and independent assessment of knowledge claims, and eventually the claim of the objectivity of science, appearing during the nineteenth century.

The principles that came to define modern science crystallized: modern science is a socially organized and institutionalized form of praxis which (a) is guided by a canon of systematic justification of knowledge claims through methodologies that give epistemic priority to the experienced and observable reality of the world, (b) explains the phenomena of the world in terms of 'shallow' explanations close to the phenomena, (c) is where knowledge claims are vetted through control processes in a community of peers, and (d) is internally and externally justified through the social (socio-technical) utilities it produces, as well as the drive of curiosity to understand the world around us.

How to define science has been, and to some extent still is, highly contentious among philosophers and social scientists studying science, even though many will agree that there is something rightfully called 'the scientific attitude' (McIntyre, 2019).[7] The United Nations Educational, Scientific and Cultural Organization (UNESCO) Recommendation on Science and Scientific Researchers (2017; from the Records of the General Conference 30 October–14 November 2017) uses this characteristic:

> *'(i) the word "science" signifies 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 interactions; brings together in a coordinated form subsystems of knowledge by means of systematic 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;*
>
> *(ii) the term "the sciences" signifies a complex of knowledge, fact and hypothesis, in which the theoretical element is capable of being validated in the short or long term, and to that extent includes the sciences concerned with social facts and phenomena'*

6 The earliest scientific disciplines arose around the late-eighteenth and nineteenth centuries; see, for example, Stichweh (1992).

7 It is virtually impossible to reference all the philosophical ideas about the essentials of what science is. Here we refer to only a few of them: Chalmers (2013), Giere (1991), Marks (2009), Okasha (2016) and Ravetz (1971). In more recent years, the relationship of science and democracy has been discussed: Kitcher (2011), Brown (2013) and Longino (2002).

For this paper, we will suggest the following shorter working definition:[8]

Science is a socially organized and institutionalized form of praxis where publicly available knowledge claims are scrutinized by peers and critically tested against empirical phenomena. The claims are derived from a multiplicity of methods, and aim to provide rational explanations and understandings of our world.

REMARKS ON SCIENCE AND ETHICS

Facts and values, science and ethics? From the historical point of view, it is ambiguous what relationship modern science, as it appeared in the Scientific Revolution, had to the claimed strict separation of facts and values, or more specifically of ethics (morality) and science. With Bacon's writings and the phrasing of the charter of the Royal Society, it seems there was a strong wish to create a clear distance from the dominant philosophies and religious ethics and morality of the time. However, the Enlightenment bears witness to the melding of the scientific spirit with the spirit of socio-political, philosophical and cultural change. For instance, Condorcet clearly believed that the sciences and technology could not progress without assuming that the morality and ethics of people would progress alongside, as both were intimately coupled.

With the dispute between the sciences and the humanities and social sciences about methods in the nineteenth century, the dispute between explanation and understanding, values and ethics was once again left outside of the descriptive natural sciences. While economics claimed values, ethics could be delegated to the philosophers. Max Weber (Weber 1946) and his thesis of value-freedom acknowledged the general value-basis of the quest for knowledge in the sciences but warned that personal values should be left outside, lest bias entered the results. The neo-positivists (Vienna circle) considered it essential that science should avoid all normative matters so that the facts of the world would not fall prey to political systems and dogmatic leaders but could form a bulwark against the lies and distortions of ideologists. Neo-Marxists, such as J. D. Bernal, called for a science for the good of the people, while philosophers, such as Habermas, described value-based functions of the social science and the humanities as separated from the instrumental technological functions of the natural sciences. In the aftermath of World War II, the call was made to protect those that are the subjects of research. This soon expanded into research ethics and the wider field of ethics of science. It was only late in the twentieth century that a few philosophers and scientists realized that (social) values were already baked into standard scientific practice, for example, in risk research and standards of proof (cf. Rudner, 1953; Copland, 2003; Douglas, 2009). Eventually, this also led to calls for a new social contract for science (Lubchenco, 1998), and for the promotion of socially responsible research and innovation (RRI). Major funders, such as the European Commission, now expect ethical issues to be directly addressed in research.

THE SYSTEMS OF SCIENCE

A process of diversification and professionalization characterized the institutional embedding of modern science in the socio-political systems of the nineteenth and twentieth centuries. What started out as 'amateur science' turned into 'professional science', most obviously initiated

8 We are aware that this normative claim is sometimes countered by empirical claims that large parts of modern science are deeply involved in the existing power structures of modern societies. Critics point out that such a normative ideal may serve to cloud the underlying power structures. However, this is precisely the reason why we separate these 'principles of science' from the 'systems of science' discussed below.

in 1810 at Humboldt University, Berlin, by the founding of research-based universities and professional positions. This prompted further developments: 'industrialized science' at the end of the nineteenth century (characterized by new industrial research bodies bridging universities and industry, such as the Kaiser Wilhelm Institute in Germany) and later 'Big Science' emerging during World War II (with external research objectives, large mixed consortia and industry-like management; cf. the Manhattan project).

Scientific disciplines as we know them today emerged only in the nineteenth and twentieth centuries (Stichweh, 1992), and they are still producing countless sub-disciplines. Even socially important subjects, such as human health and medicine, adopted the character of modern science only relatively late (roughly at the turn of the nineteenth to twentieth century). Social science was similarly not immediately ready to join the club (McIntyre, 2019).

The scientific 'ethos' ideally is the normative commitment of the community of scientists. It is based on the institutional reforms initiated by adopting the principles of science in academia. These were expressed by Robert K. Merton (1942): communism (public property of knowledge), universalism (no differentiation of nationality, race, gender, etc.), disinterestedness (expulsion of personal bias and values) and organized scepticism (examination and validation of knowledge through peers) (Mitroff, 1974).[9]

Science as a socially organized form of praxis has, as we have seen, an *internal* justification of knowledge claims, namely through some form of peer review (organized scepticism). However, it also has an *external* justification directed towards society, mainly by reference to useful insights, the *utility* directed not necessarily to those who produce or embrace the knowledge, but utility for the others, the users. Technology is one such utility. We can add another justification here, one that is assumedly still a major driver for many scientists: *curiosity* and the ensuing satisfaction when one understands parts of the world around or within one.

These ideas have become baked into a very specific socio-political framework, a framework, though, that also has changed considerably over time. What in the early days of the Scientific Revolution was a multitude of soft ideas, has now turned into hard socio-political facts. Behind this is power and concrete interests. On an even deeper level, there were vague beliefs and worldviews underlying these social processes that were to turn the principles of science into concrete institutions, supported by useful ideologies.

One of these ideologies was the belief that these new sciences would eradicate all subjectivity and the world would be studied in a fully objective manner. The individual gradually disappeared from the product of science (the publication itself) but became the hero of the discovery and the process.

Another belief was the idea of the potentially infinite progress of scientific knowledge that would provide a steady flow of useful innovations. Holders of scientific beliefs and professional practitioners of the sciences were also given a high social ranking, while other knowledge holders, say farmers, were clearly a lower rank in social hierarchy.

One important development for the later systems of science occurred just after World War II when Vannevar Bush (1890–1974), at the request of the American President Roosevelt, published the report 'Science, the endless frontier' (1945). This outlined a programme for postwar scientific research. It argued that 'new products, new industries and more jobs require continuous additions to knowledge of the laws of nature. … This essential, new knowledge can be obtained only through basic scientific research' (ibid.). This was the signal to politics to become more involved in science and, in particular, take hold of the science funding systems to steer development towards politically embraced goals, mission-oriented science. The state thus became the defining entity

9 This ethos should certainly be read as a normative appeal, not necessarily as a good descriptive account of the praxis of scientists, as I. Mitroff (1974), among others, observed.

for institutionalizing science and funding research.

With widespread colonialism, the Western model of institutionalized science systems was exported to the rest of the world. Nobody saw the need to even try to relate this new system of science to a locally existing culture of knowledge. This was also reinforced by the then-dominant belief in the inherent superiority of white and Christian European societies. Universities and institutes were (and still are) established all over the world, copying the system that operates in the Western world. Political structures and governance schemes were integrated in it. Along with this, came many of the biases and prejudices that were part of this world, acting to the detriment of the development of science. For a very long time, higher education and scientific careers were seen to be the privilege of the male gender. Even now, the sciences struggle to free themselves from the effects of gender discrimination. In addition, the science of the Global South struggles to gain its rightful visibility and integration in global networks. All too often the status, visibility and attractiveness of a scientific institution are the result of geographical location and economic prowess, rather than quality. The sciences often displayed (or display?) a disregard for other knowledge systems and typically consider other knowledge traditions as, in principle, inferior. This judgement is based upon the ideology of objectivism. We read the call for a de-colonialization of science not as a call to throw out the principles of science which are universal, but as a timely call to weed out the counter-productive remnants of the socio-political framework of the nineteenth and twentieth centuries that spread and institutionalized the scientific system and its ideology. Instead, we should look at what the principles of science can produce and what they cannot. The same should be asked of other knowledge systems. We need to abstain from pejorative rhetoric and ask the pragmatic questions of what different sources of knowledge can contribute and what research methods could bring us closer to a robust solution to deal with our problems. We also need to recognize how all societies can gain benefits when our science has access to diverse sources of knowledge.

To summarize: the principles of modern science may be universal, but they also gave rise to a relatively uniform system of science embedded in socio-political institutions (e.g. universities or research institutes). At the same time, this institutionalization often suppresses and colonizes other knowledge traditions and has introduced several culturally based prejudices and biases into an institutionalized framework which claims to be objective. The science systems of today are struggling to free themselves from these limiting prejudices and biases.

WHAT SCIENCE IS NOT

There are some themes that are perhaps worth mentioning as a contrast to the above. The questions of: (a) *truth*, (b) *uncertainty*, (c) *objectivity*, (d) *universality* and (e) *power*. These are themes that sometimes enter public discourse about science, but often are seriously misunderstood.

a) The term ‘truth’ is an element of the classical definition of knowledge: knowledge is justified true belief. We have already commented on the permissible justifications of scientific knowledge claims. But what about truth? Some have advanced the definition of science as a systematic search for truth. Obviously, science does not search for falsity, and empirical methods attempt to weed out any falsities as soon as they occur. Many philosophers have conceded that, in reality, science may never reach the final truth. Popper, for instance, talks about truthlikeness/verisimilitude (Popper, 1963), but despite some strong logical contributions to clarifying this term (e.g. Niiniluoto, 2002, 2012, 2017) as a basis for scientific progress, it seems that philosophers remain caught up in their principal choices between some form of realism versus forms of instrumentalism and forms of empiricism. In addition, scholars of science and technology remain inherently sceptical to normative or evaluative notions like scientific progress and truth. Our point here is that we can very well do without any reference to truth, and science is not the sole contender for possession of the important truths of the world. The views of science do not provide answers to all the questions that count for people. We propose the view that science aims to advance knowledge of high *quality* where quality is understood as being *fit-for-purpose*. The purposes that science pursues are, as we have said, either of a practical nature, a technological utility, or of an epistemic nature, increasing understanding and satisfying our curiosities.

b) Science does not only develop and evolve in society, but most of the time it progresses. It reaches new forms of understanding and technology, representing and intervening (cf. Hacking, 1983) with nature. We develop knowledge but with every new piece of knowledge we also develop new uncertainties. Opening up new spheres of reality means encountering new questions and problems we do not have answers to. Scientific knowledge should not be equated with certainty. Uncertainty belongs to and is a steady companion of scientific knowledge (Funtowicz and Ravetz, 1990). Communicating this uncertainty to others is as important as communicating the positive insights science produces. The existence of uncertainty is not a drawback for science, but communicating these uncertainties is a hallmark of its integrity.

c) Objectivity is often claimed to be the mark of scientific knowledge. The opposite of objectivity is subjectivity. Yet, current research in the philosophy and socio-historical studies of science has convincingly shown that scientists will always be influenced by personal perspectives that are value based and introduce a subjective bias (Douglas, 2009). This often starts with the representation of the problem they wish to address. Problems will typically be framed in terms that accommodate their disciplinary training rather than how they are framed by others, be they from other disciplines or from the general public or policy arena (Saltelli et al., 2020). Scientists are often limited to reducing the problem to what they can capture with their tools and terminology. They may enter with a tunnel-view of the problem they are addressing. This is then reflected in what they regard as relevant *pro* or *con* arguments in the ensuing publications. It is typically also reflected in information they address to policy-makers or other social actors. There is perspectivity in much of science, and this often conflicts with its inherent pluralism. While scientific standards discourage outright subjectivity and seek to capture the world filtered through impersonalized methods, this does not mean that all subjective factors and biases are totally weeded out and pure objectivity is gained. To understand science and scientific information, we need to break through the shielding rhetoric of 'objectivity' – a way of relating to the world, which in the nineteenth century was meant to replace the dominance of subjectivity (Daston and Galison, 2010). Although the goal of the culture of objectivity has always been to remove the subjective human – for instance through the mechanical means of representation, measurement and calculation; by using cameras, digital calculators and computers instead of the eye, hand and brain –, complete objectivity has proven an illusion (Daston and Galison, 2010). Scientific problems are always pursued with a degree of perspectivity (Giere 2010; Saltelli et al., 2020). As Douglas (2009) points out, there is nearly always an inferential gap between what is known and what is concluded. Further, judgement is required on the sufficiency and quality of evidence whenever a scientific conclusion is reached.

d) Universality has been expressed as a defining feature of science since the Scientific Revolution. Merton (1942) included it as one of the four core virtues of the scientific ethos. But here it is important to distinguish between the principles of science and the conduct of science systems. The former, we would argue, are indeed universal, the latter clearly are not. Universality may count as a regulative idea for scientific enterprise, yet, this should never imply that the specific science system is built upon an inherent claim of supremacy over all other knowledge for all areas of life. Like objectivity, one may thus claim that universality remains an ideal in science but is hardly a description covering all its current praxis.

e) The last remarks also speak to our final category: *power* of and within the research community. Socially, the scientific community is structured in a hierarchy of power (Brown, 2021). Where the scientific community moves is often determined by a small class of powerful people, many of them from within science but some from outside science, from industry or politics. Power and status also influence communication to the public and to policy, and even within the science system itself. This is rarely mentioned explicitly but is an aspect of its social structure that influences the kind of scientific knowledge that is produced in the end (Ravetz, 1971).

Furthermore, the scientific system itself exerts some power within the socio-political world. In the media or in political rhetoric, it is often framed as 'science shows…' or 'scientists have found…', indicating a certain authority over an issue. Yet the issues presented in this way are often also the subject of debate and disunity within the scientific community. The differentiation between a large consensus in the scientific community (e.g. evolution, climate change, etc.) and more isolated findings or opinions are often neglected in public communications.

Robert Merton and Harriet Zuckerman have observed the *Matthew effect* in science: those that have already accrued fame and funding to a significant degree are more likely to accrue more of it than others without this profile, even when their substantial research contributions are similar. Fame is typically reflected in the number of citations and visibility. Funding refers to the fact that those who have earlier acquired substantial funding will also be more successful in later funding applications. The effect has been shown to work on individual scientists, on groups (e.g. a laboratory), on institutions and universities, as well as countries. Political power structures can also affect processes for which the scientific community claims sole authority. The Lysenko affair (Joravsky, 1962) was made possible through a political system. Currently many scientists fear that political correctness (and sometimes even outright repression) may negatively bias the reporting of research (e.g., unwelcome research about environmental pollution, the selection of politically sensitive topics, or academic curricula themselves).

HOW CAN WE CHARACTERIZE INDIGENOUS KNOWLEDGE SYSTEMS?

> *'Indigenous knowledge systems are a body of knowledge, or bodies of knowledge of the Indigenous people of particular geographical areas that they have survived on for a very long time' (Mapara, 2009, 140).*

Human knowledge was always originally Indigenous knowledge. One feature of what we now call Indigenous knowledge is that it designates a passionate experience of life, a life within a community and within an environment. People relate to and modify their environment through language and artefacts – and knowledge is implicit in these interactions. Knowledge is then also place based, relative to a locality. The very distinction between knowledge on the one hand and belief on the other is a relatively late Western cultural invention. For instance, in many Indigenous societies it only emerged when meeting 'European culture' (Zegeye and Vambe, 2006, 354). Indigenous knowledge is not static, it adapts and changes over time. Even though the authority of elders and others play a role in transmitting this knowledge, this does not imply that these transmissions were blindly or uncritically adopted. Knowledge had to work in practical life.

In our times and within the Western culture, it was the philosophers with their classic definition of knowledge as justified true belief (cf. Plato's *Theaetius*) who sometimes led to misconceptions of Indigenous knowledge as irrational, while the sciences were portrayed as the epitome of rationality. But when we look closer, this is not well-founded (Kaiser, 2000). Given the principal fallibility of even the best scientific knowledge, it would be presumptuous to claim that science always has the best answers to whatever concrete problems we have in the world. But Indigenous knowledge is also fallible. Thus, when researching good solutions to complex societal problems no knowledge system should claim *a priori* superiority. The default attitude should be one of critical openness to discuss what makes a reasonable response to the given problem (Cole, 2017). Respect towards other systems of knowledge without uncritically adopting them should be a dominant value in the science systems we have. But it is impossible to conflate knowledge systems – they are based on different framings and principles.

WHY SCIENCE MATTERS

As we have argued, useful knowledge comes in many forms and in many socio-cultural embeddings. Science is one of those sources of knowledge, and a relatively reliable source, one with an inbuilt mechanism of accountability and integrity in relation to the empirical foundations of its knowledge claims. We have described the evolutionary and cultural importance of knowledge in all human populations and cultures. We explained that the principles of modern science emerged only later in history and characterized them. Then we discussed different systems of science where the practice of science was institutionally determined. We have also mentioned what we believe is often falsely claimed as the kernel of the scientific enterprise. We now need to flag what we think makes up the positive features of science that privilege them for policy advice and public acceptability.

The main features that make scientific knowledge an important and often indispensable input to policy and citizen's decision-making are:

- *Science is relatively autonomous and independent*. Admittedly, there is not a single scientist who is fully independent and autonomous. None of us is ever fully independent. In many places there is political pressure on scientific institutions; scientific findings can be highly unwelcome and politically problematic for those in power. But in science, the system and practice are designed to notice this and fight against suppression of unwelcome or inconvenient knowledge. Scientific institutions generally oppose threats to their autonomy. The ISC (and its predecessors) has a history of promoting international exchange of scientific information across political divides, and of supporting scientific freedom on a global scale. We know of no other knowledge culture with a similar radical stance on freedom, autonomy and independence.
- *Science produces knowledge as the result of organized skepticism and empirical or logical quality checks*. Knowledge may sometimes emerge from an individual, but scientific knowledge is never certified based on authority alone. While pure objectivity may be an illusion, and some bias can be found in all walks of science, there still is a systematic effort to weed out idiosyncrasies and claims that lack empirical support. The threshold for acceptance of knowledge claims into the body of scientific knowledge is – generally – rather high, and therefore the reliability of the claims is also relatively high.
- *Science produces new data quickly, responds to new phenomena and seeks coherent integration into the existing body of knowledge*. Adaptivity to new situations is perhaps one of the features that best differentiates science from other knowledge systems. Thus, scientific knowledge evolves rather than being embedded as dogma. Scientific research is particularly sensitive to data and phenomena that run counter to accepted knowledge. Science is always on high alert towards possible falsification – that is empirical data that does not fit with established thinking and prompts changed understandings.
- *Science explains phenomena based on systems of natural causes and natural entities, and refrains from reference to higher powers or religious beliefs*. Many who engage with, or study science do this out of curiosity and the drive to understand the world around us. To the extent that science comes up with explanations of natural phenomena, these do not require quasi-religious transformations of beliefs, but at most an assessment of likelihood and sometimes

simply an understanding of a causal mechanism. Science stays away, as far as possible, from religious or ideological battles of belief, and this makes science particularly well-suited for policy in modern pluralistic democracies.

While there may be many more features that show why science matters as a reliable and strong source of knowledge,[10] we think these four features justify a key role for science in informing policy and enhancing civic understandings. They show a qualitative difference to other sources of knowledge without giving rise to any form of scientific hubris. None of the above features guarantees better results than other knowledge sources, but together they show how a neglect of scientific knowledge may put us on the wrong path altogether. Science matters, certainly for our public policies, but in the end also for our individual lives.

PART 2. THE ROAD TO TRANSDISCIPLINARITY

WHAT IS THE RELATIONSHIP BETWEEN SCIENCE AND ACTIONABLE KNOWLEDGE?

Thomas Kuhn (1962) introduced the concept of 'normal science' into discourse about the workings of science. Normal science, in his conception, was based upon paradigms which defined the puzzles and methods with which the scientists worked in their discipline. Typically, they did what we also describe as 'basic science'. Realizing the potential consequences of their knowledge for aspects of our practical life, they sometimes appended the term 'applied' to some of their disciplines. In the aftermath of World War II, the external socio-political demand for this kind of application of scientific knowledge increased. But society also demanded some form of control of the risks that science and technology produced as unintended outcomes. Chemical pollution, nuclear power and genetic modification are examples of technologies that demand external means of control. The new fields of risk studies and system analysis were born. Here, the limits of what normal science, the traditional disciplines, could achieve were realized. Regardless of how sophisticated model design was, it often could not capture the complexity of the whole problem.

Eventually, we also learned that not all problems could be solved by science. Alvin Weinberg (1972) talked about *trans-science* in relation to problems that could be formulated in terms of science, but with solutions that extend beyond the means of science (his example was the effects of low-dose radiation). Horst Rittel and Melvin Webber (1973) described what they called '*wicked problems*' as a typical challenge in planning and social policy: 'Problem understanding and problem resolution are concomitant to each other.' Wicked problems have no definite problem formulation, are always multi-causal, multi-scalar and interconnected. There are no true or false solutions to them, only better or worse answers, and there is no stopping rule for when a problem can be regarded as solved. This new social reality introduced an impasse between science and action.

Against this background of complex systems, Silvio Funtowicz and Jerome Ravetz (1990; 1993) first formulated what they (with reference to Kuhn) called a 'post-normal' framework for understanding science-for-policy. The mantra of this framework was: (a) the stakes are high, (b) the facts are uncertain, (c) the values are in dispute, and (d) decisions are urgent. Post-normal

10 For a more comprehensive discussion of trust in science see, for example Naomi Oreskes (2019).

science calls for extended peer review with all stakeholders and uncertainty mapping that includes technical, methodological and epistemological uncertainties.

Such frameworks do not make basic or normal science superfluous (you still want the vaccines designed by relevant experts in immunology, or the jet engines developed by aeronautic engineers). But meeting the complex challenges and wicked problems that our society faces requires thinking outside the box, and thus breaking through the disciplinary siloes of normal science.

When science targets policy and societal action in the face of wicked problems and complex realities, the character and moral imperative of scientific communication changes significantly (for conflicting roles of scientists see, for example, Oreskes, 2015, and Benessia and De Marchi, 2017). Facts and values become intertwined, more so than in normal science. High-quality communication rests on a good understanding of what the communication must address. Communicating uncertainties can be of equal relevance as communicating positive knowledge. Furthermore, rather than seeking to optimize the output, Herbert Simon's (1979) plea for satisficing is illuminating: 'Decision makers can satisfice either by finding optimum solutions for a simplified world, or by finding satisfactory solutions for a more realistic world. Neither approach, in general, dominates the other, and both have continued to co-exist in the world of management science.'

Several observations are relevant here. The community of those with relevant knowledge to assess certain classes of claims, the 'peers', extend to sectors outside of the academic community. Stakeholders and interested parties, those that are affected by a policy, and ultimately civil society are potential contributors *and* assessors of actionable knowledge claims. Thus, to a certain extent, knowledge and politics merges as a partnership aimed at finding robust ways forward to meet the (grand) challenges of society. Consequently, institutional, ideological and compartmentalized boundaries must be crossed. A diversity of knowledge systems and experiences needs to be included. Solutions need to have democratic legitimacy and reflect the value-landscapes (Kaiser, 2022; Kaiser, in press) in society.

WHAT IS INTER- AND TRANSDISCIPLINARITY?

Awareness that mono-disciplinary knowledge is seldom sufficient for policy and action-guiding recommendations has been growing in academic leadership for a long time. Based on this awareness, important funders (like the EU Framework programmes) supported multidisciplinary and later interdisciplinary research projects. Multidisciplinary projects were built on the hope that a concerted effort from several disciplines to address a common problem might provide more useful guidance how to solve the problem. Interdisciplinary research was supposed to go one step further, namely the fruitful interaction between and across several disciplines to produce a unified approach on how to research a problem to make a useful scientific contribution that could guide actors in their efforts to deal with the problem. In effect, interdisciplinarity was supposed to be relatively innovative through close collaboration on how knowledge about an issue was produced. In recent years, many funders included a demand to consult with stakeholders when proposing actionable scientific knowledge. This then was already an important step in the direction of *transdisciplinarity*.

The Evolution of a Concept

How did the call for transdisciplinarity arise? The literature cites Jean Piaget one of the first influential voices that introduced the very term 'transdisciplinarity', as a response to the student unrest about what was perceived as petrified hierarchies and power structures in universities.

In 1970, he called for transdisciplinarity as ‘without any firm boundaries between disciplines’ (Nicolescu, 2010). The concept emerged visibly at the 1970 Organisation for Economic Co-operation and Development (OECD) conference on ‘Interdisciplinary Research and Education’ in France. Here transdisciplinarity was conceived as a common set of axioms transcending individual disciplines and broadening the scope of research.

The important element of the notion was its prefix ‘trans’, translating into ‘beyond’. It was clear that transdisciplinarity would go beyond traditional disciplines, but where to, what new sector or field would be integrated? Or was it just to be a ‘super-discipline’, a theory of everything? The term needed a promoter who could give it more clarity.

The Romanian physicist (and in effect philosopher) Basarab Nicolescu filled that role for an important part of the early 1990s (Nicolescu, 2002; 2014). He was the co-founder (with René Berger) of a study group on Transdisciplinarity at UNESCO in 1992, and in 1994 he was the main contributor to the ‘First World Congress on Transdisciplinarity’ at the Convento Da Arrabida in Portugal. He propagated a version of transdisciplinarity which was anti-reductionist, multi-culturalist and would include all humanities and social sciences. The conference resulted in a ‘Charter for Transdisciplinarity’, written very much in the style of a typical UNESCO charter. Its article 14, for instance, said this about transdisciplinarity:

> *‘**Rigour**, **opening**, and **tolerance** are the fundamental characteristics of the transdisciplinary attitude and vision. **Rigour** in argument, taking into account of all existing data, is the best defence against possible distortions. **Opening** involves an acceptance of the unknown, the unexpected and the unpredictable. **Tolerance** implies acknowledging the right to ideas and truths opposed to our own.’*

Nicolescu’s aim was to provide a concrete methodology for transdisciplinarity. He claimed that the ‘theory of transdisciplinarity is fully developed’ (mainly through his own work). His philosophical meanderings apparently found some resonance within the UNESCO structure and some transdisciplinary journals and books on the topic were published.

However, apart from some philosophical and political acclaim, Nicolescu’s approach was apparently not very influential in later years. What was influential, in addition to post-normal science, was the publication of the book *The New Production of Knowledge* by Michael Gibbons et al. (1994), and its differentiation between Mode 1 and Mode 2 science. Mode 1 research was effectively what Kuhn had called normal science. Mode 2 was here characterized as application oriented, heterogenous, and basically transdisciplinary. Yet, its transdisciplinarity derived mainly from the problem import from society. This spurred the 2000 conference ‘Transdisciplinarity: Joint Problem Solving among Science, Technology and Society’ in Zurich. Here the problem shifted from theory-driven deliberations to a new form of practice.

There is relative agreement in the literature on transdisciplinarity that there were two distinct and independent strands of the concept of transdisciplinarity: ‘Nicolescu and Gibbons et al. can be said to have spawned separate streams of transdisciplinary work ... While Nicolescuian transdisciplinarity emphasizes a concept of the human life-world and lived meanings ..., the Zurich tradition prioritizes the interface between science, society, and technology in the contemporary world’ (Bernstein, 2015, 7).

The latest influential development arose from the 2020 OECD report Addressing Societal Challenges Using Transdisciplinary Research, published in the middle of the pandemic with several case studies. In this report transdisciplinarity is defined ‘by the integration of academic researchers from different disciplines with non-academic participants in co-creating knowledge and theory to achieve a common goal’.

Current Concepts of Transdisciplinarity

There is a vast literature on transdisciplinary research, sometimes theoretical, but often also analysing experiences from concrete project work (for instance, Wickson et al., 2006; Russell et al., 2008; Carew and Wickson, 2010; Clark and Button, 2011; Pohl, 2011; Klein, 2013, 2015; Wickson and Carew, 2014; Gethmann et al., 2015; Osborne, 2015; Bieluch et al., 2017; van Breda and Swilling, 2018; Pereira et al., 2018; de la Vega-Leinert and Schönenberg, 2020; Chambers et al., 2021; Deutsch et al., 2023). There is also literature which more implicitly relates to transdisciplinarity while highlighting other terms; for example, citizen science, co-production of knowledge, sustainability science, participatory research, Indigenous knowledge integration, empowerment or similar terms (e.g. Barreteau et al., 2010; van Kerkhoff, 2014; Chilisa, 2017; Knapp et al., 2019; Anthony-Stevens et al., 2020; Shrivastava et al., 2020; Ruwhiu et al., 2021; Zurba et al., 2021; Kareem et al., 2022).

Obviously, it is impossible to review the whole literature on transdisciplinarity here or to do justice to all the specifics discussed in these contributions to transdisciplinary research. It is encouraging that there is indeed such an active global interest in transdisciplinary research. Instead, we will connect to what above was described as the 'Zurich tradition' of transdisciplinarity, and we shall highlight features of transdisciplinary research that we believe provide a general framework for (most of) the different accounts of transdisciplinary research.

Jahn et al. (2012) proposed a general definition of transdisciplinarity:

> *'Transdisciplinarity is a critical and self-reflexive research approach that relates societal with scientific problems; it produces new knowledge by integrating different scientific and extra-scientific insights; its aim is to contribute to both societal and scientific progress: integration is the cognitive operation of establishing a novel, hitherto non-existent connection between the distinct epistemic, social-organizational, and communicative entities that make up the problem context.' (2012, 9)*

Here, as in many other current contributions, transdisciplinarity is not conceived as a new (super-) theory, a new epistemology (as, for example, by Nicolescu), a specific methodology, or a new institution or discipline. It does not replace or diminish the value of disciplinary science. What it does is perhaps best seen as an attempt to synthesize various sources of knowledge with a diversity of value perspectives in the face of inherent complexity to produce actionable knowledge for the good of society. These seem to be the recognized drivers of the current deliberations about transdisciplinarity: (a) the inherent **complexity** of the world confronts us with basically 'wicked problems'; (b) the call for actionable knowledge confronts us with the **post-normal** science situation where facts and values become intertwined, and assessments need to go beyond academic peers; and (c) the production of knowledge needs to attend to problems **external** to the inner-dynamics of the **disciplines**.

One feature recognized as highly important is the sensitivity to and integration of the **context** of the research, with consideration of scope and scale (Knapp et al., 2019; Schneider et al., 2022). Cultural diversity and different governance systems necessitate pragmatic adaptations of the research design to generate actionable knowledge. The context is seldom just a given but needs to be constructed among the partners.

A recognized element to be integrated in transdisciplinarity is the **participation** of partners outside academia. The call for participation is not new nor very specific for transdisciplinarity. Participation of stakeholders has for a long time been a crucial precondition for research for development aid and technology transfer (cf. policies at the World Bank). In the social sciences, it became prominent after the move of Kurt Lewin to produce 'action research' during World War II. In general, participation aims at robust knowledge that is easily adopted by stakeholders outside the research, and it is based on a conception of a more democratic role of science in society where participation can aim at different levels of empowerment. Sherry Arnstein (1969) differentiated the different democratic aspirations in her classical ladder of participation.

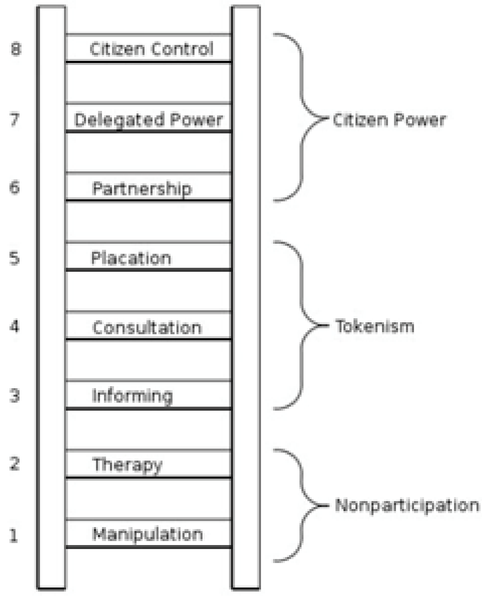

Figure 2. Arnstein's ladder of participation

Source: Arnstein (1969) https://organizingengagement.org/models/ladder-of-citizen-participation

Having these different forms of participation in mind, the question arises of what degree of participation does transdisciplinarity aspire to. From the current literature, we can safely assume that transdisciplinary research aims at partnerships, not mere consultation. Whether or not more power can result from transdisciplinary participation seems to be a function of the nature of the context and problem, governance structure and external factors, such as whether a particular problem solution is delegated to societal actors (as can be the case with self-control/internal controls of safety in large corporations, or with community actors in regard environmental protection, etc.). **Empowerment** of the affected stakeholders is a recurrent theme in the literature about transdisciplinarity (Chambers et al 2021). Inclusion of a diversity of actors, epistemic perspectives, viewpoints and value orientations is built into the demand of participation.

Another important element is that of a **shared social responsibility**. This reflects the widely shared acknowledgement that all transdisciplinary research is based on broad and shared problem framing and aims at problem resolution. Therefore, knowledge production is ultimately guided by values which are external to the more narrowly defined internal norms of the sciences. Sustainability as, for example, expressed in the recently developed Sustainable Development Goals is such an external value. In this sense, transdisciplinarity is complementary to sustainability.

A common and, we believe, wrongful claim is that transdisciplinarity effectively extends mere interdisciplinarity. We have already mentioned that it is a misconception that transdisciplinarity (or post-normal science) devalues all good disciplinary knowledge. This impression may be the result of derogatory talk about academic 'siloes'. In our understanding, the opposite is true: transdisciplinary research rests and relies on the very best disciplinary knowledge. It requires access to the rich foundation of basic science, whatever its origin. The defining difference to interdisciplinarity is the **openness to external sources of knowledge, problem perception and value commitments** that provide a potentially corrective input and supplement to interdisciplinarity. Academic knowledge in transdisciplinarity enters into a **dialogue** with external actors as an equal partner, rather than an *a priori* superior knowledge provider. The public are not only consulted in research addressing with complex societal issues, but they are integrated into crucial aspects of it. We characterized this as the empowerment ambition in the ladder of participation. Sometimes people refer to this also as *citizen science* although that often encompasses activities that are not necessarily transdisciplinary. Much citizen science engages citizens in what is still mode 1 research (for example, in data collection).

This discussion is admittedly not without potential and indeed real conflict when scientists are confronted with alternative knowledge claims, based on alternative knowledge systems. This can happen in societies with strong Indigenous cultures, maintaining Indigenous knowledge systems. Indigenous knowledge systems do not comply to principles that define standards of scientific quality and validation (experiment, peer review, shallow explanations, etc.). They are to a varying extent based on experiential knowledge (which may be lost in time), accumulated in long traditions and communicated by trusted elders. This is precisely the point when the call for increased reflexivity in transdisciplinarity should set in.

We argue that any inbuilt hubris related to the knowledge system you are working with should be overcome. This is very much in line with the call for increased **reflexivity** in transdisciplinarity. The notion of *bias* is well known within science and within belief systems in general. There are many forms of systematic biases, some innate and some learned. Cognitive biases come about because people create their own social reality from their personal perceptions and expectations, cultural world view, training or social standing. Typically, a cognitive bias distorts the available evidence and can lead to false interpretations. However, some such biases may originate in an evolution-based simplified information process in the brain, which allows speedy choices in complex decision situations, and some such biases may be adaptive over time. Social psychologists have studied many forms of bias, with framing (i.e. the social construction of how an issue is presented), anchoring (i.e. favouring the first pieces of information for decision-making) and confirmation bias (i.e. favouring conforming evidence over contradicting evidence) being quite widespread even among academic experts.

Transdisciplinarity identifies the occurrence of these biases as a major issue that hinders the cooperation of different social groups and stakeholders towards a common goal of decision-making and problem solving. Kahnemann and Tversky showed bias in academic experts, and later Kahnemann, Gigerenzer and others argued that bias may not always be counter-productive when decisions on complex matters are urgent (cf. e.g. Gigerenzer, 2008; Kahnemann, 2017; Todd and Gigerenzer, 2000). However, when these biases remain unrecognized in a group of actors working towards the solution of a common problem, they distort the recognition of the contribution of others. Reflexivity is therefore a crucial characteristic of transdisciplinarity.

A common misunderstanding is that transdisciplinary research is mainly for the natural sciences, economics or medicine, including some sectors of social science, but tends to leave out the humanities and more foundational work from the social sciences. Osborne (2015) claimed that current versions of transdisciplinary research tend to overlook contributions from the humanities and philosophy. He based his thesis on critiques of disciplinarity which occurred early in French and German philosophy and cultural studies. However, we see a clear role for the humanities and social sciences in transdisciplinary research. Conceptual analyses, normative studies of argumentation and communication, and foundational work regarding the history and power aspects of cultural and socio-political ideologies can significantly enrich our understanding of the complex issues we face in transdisciplinary research. Art and literature have been proven to enrich understanding and visions in extended peer communities. Ethics must be integrated both in the subject matter and roles in the partnerships and conduct of the research. It is regrettable that humanities and some social sciences are often neglected in current transdisciplinary research and we would plead for a much more extensive integration of such work.

To summarize, ***transdisciplinarity*** is clearly distinct from other forms of academic collaboration (as e.g., multi-, or interdisciplinarity), and does not imply any kind of new super-theory, new epistemology, or revolutionary methodology. It does, however, present a principally different approach to addressing ***complex societal and 'wicked' problems*** in their relevant ***context***. The most crucial difference lies in the conception and task of the ***partnerships*** that work together towards a mutually recognized solution that is ***fit-for purpose*** and respects basic value conceptions ('value-landscapes') in society. ***Dialogue*** constitutes these partnerships, and such dialogues will have to be pragmatically adjusted to the cultural and socio-political

context of the research, with particular attention given to the ***scope*** and ***scale*** of the issues. Transdisciplinarity always implies a multi-actor ***approach*** with a principal ***openness*** towards what belief, knowledge and value systems are considered relevant for the task at hand. Knowledge systems require the inclusion of social science and humanities, but also extra-scientific belief systems like Indigenous knowledge. Genuine ***citizen and other stakeholder participation*** is a cornerstone in transdisciplinarity. Developing a ***common language*** is one of the primary tasks of such partnerships. The partnership recognizes a shared *social responsibility* to respect and work towards common or important social values, respecting and enhancing democratic legitimacy. A precondition of transdisciplinarity is mutual ***reflexivity*** with the willingness to lay bare the inherent cognitive and other biases of all actors, resulting in either the elimination of these biases or the constructive recognition of their contribution to mutually endorsed solutions. Recognition of the relevance of making a ***timely contribution*** aimed at ***socially responsible*** impacts constrains transdisciplinary work.

THE PRACTICE OF TRANSDISCIPLINARITY

It is unrealistic to pre-define all the concrete aspects of putting transdisciplinarity into practice, other than by appeal to the above-mentioned overall values and goals (cf. also Hadorn et al. 2011). However, that does not imply that some form of guidance could not be useful, especially given the abundance of research that seeks to contribute to policy. This is also true in relation to the demands by different constraints on funding such research. Transdisciplinary research need not always be either initiated or led by an academic institution; civil society groups could well be in the driving seat. We shall now address some such guidance.

First, we need to ask if transdisciplinarity enters all phases of research. The simple answer to this is 'yes', albeit in slightly different ways. How to structure the different phases in transdisciplinary research differs among authors. Carew and Wickson (2010) presented a 'TD wheel' (see also Appendix 1), which aims to support the research in 'shaping (planning and proposing research), supporting (guiding research in-train); and evaluating (planning for evaluation, periodically documenting / checking progress, and reporting outcomes)' (ibid., 1146). Context emerges here as the dominant driver of process and product. Other authors (e.g. Jahn et al., 2012; Verwoerd et al., 2020) propose slightly different conceptions. Here we roughly characterize the research by its five most crucial phases (Figure 3).

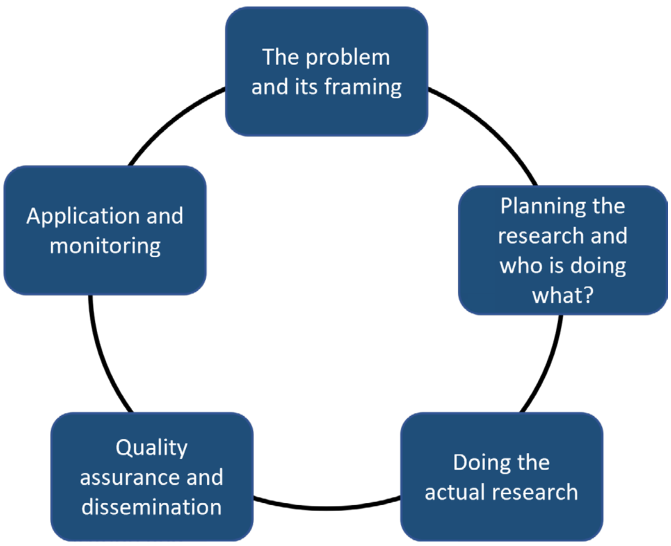

Figure 3. Phases of research: -We depict scientific research as an endless pursuit.

Claiming that transdisciplinarity is collaborative research within partnerships implies that dialogue between partners enters all phases of the project, perhaps most crucially in the framing of the problem and the quality assurance of proposed solutions. However, splitting some tasks to different groups in different phases need not inhibit the overall quality of the research. Indeed, given the recognition of the importance of different knowledge systems, it might be useful for some of the groups to work out their perspectives separately before they enter the common dialogical effort. The natural scientist might pursue model-building on parts of the system, the social scientist might look at the socio-cultural or economical embedding of the system, the humanities scholar might add historical dynamics, while practicians search their professional experiences, politicians their option-space for action, and Indigenous groups consult their traditions and wealth of transmitted experiences. The important point is, though, that groups come together repeatedly seeking commonalities, synergies and integration.

In later phases of the research, for example, in quality assurance and dissemination, non-academic actors may have a more dominant role than purely academic actors, depending on the issue and its applicability and value-embeddedness within society. Research results may well be owned by the non-academic partners.

In line with the ISC report, 'Unleashing science' (which speaks to mission-oriented science), there must be a continuity and integration of the work tasks within a transdisciplinary research project:

> *'Mission-oriented science does not end at proposing the implementation of transformative action, but must be actively engaged in the tracking, analysing, understanding and course-correcting of changes set in motion, so that the dynamics of change can be nudged in overall desirable directions' (International Science Council, 2021, 30).*

Second, the nature of the issue may necessitate stepping out of well-entrenched and predetermined research methodologies and seek out new forms of knowledge generation. This is particularly the case when a problem calls for some (technical or social) innovation or more holistic embedding. Here some groups have successfully experimented with *open innovation and innovation-labs/ living-labs*. Others have tried to bring ideas from citizen science to life to engage citizens not only in the gathering of relevant data or background information, but also in shaping new questions, new knowledge and new solutions. Knowledge-to-action-networks are an example of this (Steel et al., 2017). Many have extended dominant forms of what counts of expertise in, among others, systems for *adaptive management*. *RRI* shares many of the characteristics of transdisciplinarity, for example, addressing significant socio-ecological needs or focusing on mutual learning among various actors. In all of this, we can recognize some overlap of transdisciplinarity with other research schemes, many of which are encouraged by funders, stakeholders or NGOs. Transdisciplinarity is surrounded by relevant new approaches that easily, at least partially, integrate into the frame of transdisciplinarity, as depicted in Figure 4.

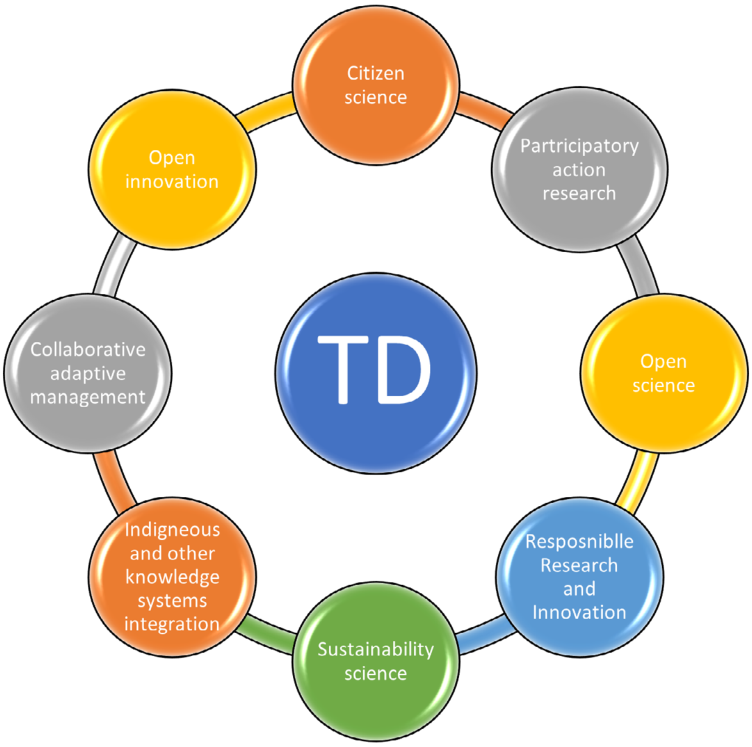

Figure 4. Transdisciplinarity (TD) related schemes of scientific research

This highlights the (partial) overlap between several current ways of defining socially relevant transformative research (Knapp et al., 2019). To pick one example, the recent focus on Open Science as highlighted by the EU, UNESCO and the ISC typically depicts the inclusion of extra-scientific knowledge systems and the participation of civil society as important elements of the science needed to reach important societal goals, like the SDGs. The UNESCO 'Recommendation on open science' (2021) talks about 'open engagement of societal actors' and 'open dialogue with other knowledge systems'. Both are decisively a hallmark of transdisciplinary research.

PART 3. MAKING TRANSDISCIPLINARITY REAL

Discussions about transdisciplinarity are not new, as we have seen. Recent attempts to provide guidance for transdisciplinary research are motivated by the wish to strengthen the link between knowledge and action, to prepare the ground for transformative research projects with robust solutions. Given the great societal challenges our world faces, there is an urgent need to reform and improve research systems to realize sustainable changes . As we discuss below, we need to address many structural and institutional impediments to effective transdisciplinary research.

The ISC has recognized this need for some time. It engaged in pioneering transdisciplinary research programmes between 2014 and 2022. These were: Transformations to Sustainability Programs T2S 1 and T2S 2, followed by the Leading Integrated Research for Agenda 2030 in Africa (LIRA 2030). All three research programmes sought to achieve transformative knowledge through transdisciplinary approaches, and to integrate the contributions of the social sciences and humanities. Building up capacity and leadership in the Global South was a further objective. The results and lessons from these programmes will be summarized in a forthcoming book, edited by Roderick Lawrence, *Handbook on Transdisciplinarity*, and detailed in a chapter on 'Advancing transdisciplinary research in the Global South' (by Paulavets, Moore and Denis). Further, partnership with the Belmont Forum and its transdisciplinary programme Pathways is promoting the practice of interdisciplinarity.

We need to go beyond business-as-usual to seek out new structures for mission-oriented research and funding, supporting such research as, at the global level, the ISC report 'Unleashing science: delivering missions for sustainability' (2021). Here there is a dramatic mismatch between science funding and global research priorities, while co-design and transdisciplinarity are recognized as important tools for transformative research. Important in this report was the realization that the current science system 'is structurally *inhibiting* science from making a significant contribution to achieving the SDGs' (ibid., p.26). Given its focus on global challenges, the report argues for new funding mechanisms for multi-lateral research, but also notes that new thinking and new funding models need to be developed in all our science systems (cf. also Schneider et al., 2021). The ISC itself is leading work towards new models (cf. International Science Council, 2022).

In the academic literature, there are scant contributions on funding requirements for transdisciplinary research and co-production (Arnott et al., 2020), on funding and evaluating actionable knowledge (Mach et al., 2020), on evaluating inter- and transdisciplinary research proposals (Pohl et al., 2011; Belcher et al., 2016) or on the need to separate a seed-grant period from a full funding of a developed research proposal (Moser, 2016).

We share many if not most of the insights in these sources, even though we suspect that our stress on inclusion of both epistemic and value diversity in transdisciplinary research may go further than elaborated in several of them. However, a common theme in all of them is the need for structural reform in the funding schemes for transdisciplinary research as well as the criteria for evaluating both the research and the researchers engaging in this research. Capacity building, learning and training also provide a common challenge.

HOOK ON TO OUR COMPLEX REALITY

In the literature, several contributions seek to provide concrete guidance on the design of transdisciplinary research. As examples, we present three such proposals in Appendix 1 (Carew and Wickson, 2010; Jahn et al., 2012; Renn, 2021).However, in the following discussion we will address the institutional and science system barriers that must be overcome.

There are indeed an impressive number of past or ongoing national research projects, which live up to some of the ideals of transdisciplinary science. A recent workshop at the Metochi Study Centre on Lesvos gathered some interesting transdisciplinary projects, funded within national programmes (cf. Murvold and Kaiser, 2022). Surely many more could be added. We are also aware of interesting work going on in the Global South, for example, the SAEON Maputaland project[11] which is a good example of short-term (3 years) transdisciplinary research design, but several others could be added (cf. Mapara 2009; Chilisa 2017; Breda and Swilling, 2019; de la Vega-Leinert and Schönenberg 2020; Zurba et al 2021; Kareem et al 2022; Schneider, 2022).

While these examples illustrate both the innovative designs of the research and the high motivation of the (mostly young) researchers involved in them, their funding restricts a catalytic impetus

11 Ramjeawon, M., Demlie, M., Toucher, M.L. & Janse van Rensburg, S. 2020. Analysis of three decades of land cover changes in the Maputaland Coastal Plain, South Africa, Koedoe 62(1), a1642

from knowledge generation to societal change. As noted above, the reasons for this are systemic in our current systems of science. Scientific institutions and their funders may share the goals of transdisciplinary and transformative research and encourage the production of actionable knowledge, but their funding schemes and quality assessment criteria are inadequate to cover the various phases of transdisciplinary research over longer time periods. One stumbling block is quality and its assessment. Criteria of merit and excellence as used in mode 1 science cannot address the special challenges of transdisciplinary research, and measures of impact – as they sometimes are employed in innovation projects – are difficult to employ along the lifespan of a transdisciplinary project. New thinking is required, and we will attempt to illuminate the special challenges. In particular, we will try to cast more light on the difficult task of how to assess the quality of transdisciplinary research. One way to do this is by way of an in-depth discussion of an example, in our case a fictional example, of one type of transdisciplinary challenge of medium scope and scale.

The Example

Newasaria is a province of a federalized democratic state. It is largely defined by the Newar river that runs from heavily forested hills though a broad floodplain into Newar Harbour. Newar City, the provincial capital, lies at the river's exit into the harbour and has grown in recent years into a significant city. There have been small communities engaged in subsistence agriculture and fishing along the river for at least 1000 years. They have developed their own traditions and culture. For several decades, the upper river cascading through the forested hills was promoted as a tourist attraction with salmon fishing and hiking trails. The harbour itself was also promoted for sea sports and fishing, and in places marine farming of oysters had grown to be a significant export industry.

But in the past 70 years the flood plain has become dominated by industrial-scale farming, a mix of dairying and intensive horticulture. Three times in the last 15 years there has been a toxic algal bloom, which has meant shellfish farming had to be suspended and was eventually abandoned, causing considerable anger and economic loss. In the face of rising unemployment, the province attracted a paper mill to be established at the base of the foothills and gave the mill owners rights to mill considerable areas of the forest, which they have converted to dairy and cattle farming, restricting hiking trails.

The Newar river has become increasingly polluted. Some of the pollution has occurred because of upstream hardwood deforestation for cattle farming – but the productivity is low and considerable amounts of nitrogen- and phosphate-rich fertilizer has been used to improve productivity leading, through runoff, to eutrophication in the rivers and streams. The geography is such that land pollution has led to large amounts of sediment being washed into the river. At the same time, the number of sawmills along the river, including one paper mill, have led to deforestation and heavy metal contamination. Local communities, who enjoyed fishing on the river, have lost income from the fly fishers who have stopped coming to a river once famous for salmon fishing. Tourism has declined greatly.

There are rising demands to clean the river, which is now eutrophicated and polluted by sediment, heavy metals, wastewater and plastic rubbish. At times Escherichia coli levels in the water at the exit into the harbour have been high due to sewage overflow from the ageing infrastructure of the city. The blame game has become particularly heated among the traditional communities, the farmers, the sawmill operators, the city government, the tourist industry and the fishing industry. Protests are common, fuelled by social media, and it is now the dominant political narrative.

The local government has stated that the river must be cleaned up, claiming that in doing so tourism and the economy will be restored. They wish to put planning regulations in place restricting landowners from tree cutting and limiting fertilizer use. Both farmers and local service communities that depend on farming as their primary income source oppose restrictions on farming and argue the real culprits are sawmills and factories. The farmers also argue that much of the pollution comes from urban and industrial runoff from Newar City.

The last election was fought over claim and counterclaim as to the causes of pollution and a general demand from all concerned that water quality be improved so that recreational and commercial use of the river and harbour can return. Each set of actors claimed a singular action by others was the way forward.

In response to a national grant call for large-scale research projects with a focus on environmental issues, Newar State University (NSU) submitted a grant application to address the issue. It claims that a systems based transdisciplinary approach is necessary to find a way to address the quality of water entering the harbour.

The university-led submission stated that the first phase of the research programme would be a multistakeholder dialogue with all partners and academics from social science, forestry, agronomy, marine science and urban planning. Particular attention would be paid to inclusion of stakeholder groups and dialogue with the traditional upstream communities, farmers and fishers, and those in more authoritative positions. They proposed that the output of first stage would be a 'systems map' of the issues as agreed by all stakeholders. Form this, they would identify what empirical research would be needed to progress towards multiple and acceptable partial solutions.

Even in submitting the grant, the applicants faced institutional difficulties. The research administrators at NSU were concerned that some of co-investigators were not academics, that the knowledge produced would not fit well with the metrics-focused national university ranking system and that the knowledge produced might lead to exploitable value but this would not be to the University's direct commercial advantage. The research vice-president of the university expressed his scepticism of a grant application that did not detail specific protocols for empirical research. As a result, the principal investigator faced multiple challenges getting internal approvals for the application with numerous logjams over issues such as intellectual property (IP) agreements, funding arrangements, indirect costs and more. Several department chairs expressed their concerns over their junior faculty being involved, as it might compromise their tenure chances by being involved in research which would not produce 'high-impact academic papers and which moved beyond the boundaries of their academic departments'.

Beyond the obvious institutional barriers which appear difficult to remove in the face of persistent conservatism as to what makes for impactful research, this type of problem generates several related problems for a science system. How should a research application such as the one proposed be assessed for funding? How should the academics involved be assessed? How should its outputs be assessed? While potential transdisciplinary challenges will be diverse, many of the issues they face are generalizable, particularly for matters involving the university and institutional funders. We will focus on these dimensions in the discussion that follows, recognizing that there are other questions that need to be asked from the perspective of non-academic stakeholder.

CONSIDERATIONS FOR THE GRANT FUNDING INSTITUTION

Both the public and the policy community expect that knowledge disciplines should address complex issues such as societal resilience, public health and sustainability with their expertise. Many governments have multiplied their investment in research and development (R&D) in expectation of solutions to many issues. However, delivering these through disciplinary sciences has been disappointing, in part because reductionist approaches often do not deal well with issues such as scalability, acceptability and societal responses and thus translation to impacts. Impactful knowledge on issues relevant to contemporary societal and environmental challenges often requires transdisciplinary approaches to move beyond just diagnosing problems, and to produce better embedded outcomes with a realistic chance of impacting public and policy understandings and solutions.

We have given the example of Newasaria and its river to illustrate this complexity, also to stress that these problems arise not only at the global level, as with climate change, but often have a very clear local profile.

If science is to employ transdisciplinary research to a larger extent, it needs the appropriate funding mechanisms. Many public funders of science (research councils, academies, etc.) elicit calls for research on several of the grand societal challenges but do not always understand that the system of assessment must be distinctive. Many mention potential impacts on public policy as an explicit goal that should be envisioned by such research. Furthermore, many funders also include the involvement of 'end-users' through participatory research as a condition of funding. The EU Framework programmes for science include references to Open Science, RRI, ethics and participation.

But such institutions generally fail to meet their promise. The reality is that the societal aspects often end up as an appendix, as an isolated patch of research adding to the work of natural scientists and engineers. This linear approach sees consideration of impacts, policy and social engagement as 'downstream' from academic research. What many have realized is that for the types of complex problem we are considering, the research needs to be holistic from the start, and that one needs integration of these impact and engagement dimensions 'upstream'. This is precisely what transdisciplinarity tries to achieve. For this to happen, funders should develop mechanisms and guidelines that support transdisciplinary research. Transdisciplinary research proposals require 'significant time to build the kinds of constructive working relationships necessary for coming to agreement. This need for patience and years of time does not, of course, fit well into current political election cycles of two to four years' (Steel et al., 2017, 210).

We assume that a funder, for instance, a public research council, has come up with a fitting call and that a transdisciplinary proposal has been submitted.

Beyond assessing the proposal (as discussed in the next section), the funding body must consider:

- *The length of core support, whether they would allow incremental funding and what would be intermediate outputs that would allow such funding.*
- *What is the governance and management of the project?*

The first point relates to the projection that transdisciplinary projects will have a longer lifespan than ordinary research proposals. But since they also go through different phases, the outcomes of which are hard to predict from the start, the research may have to be funded stepwise. There needs to be an expectation in engaging in phase 1 that there is a high probability of moving to phase 2. Otherwise, the effort expended to build trust between the knowledge communities will be undermined and that loss may have long-term echoes. This, in itself, is not a totally new concept as there are similar mechanisms, for example, for the funding of centres of excellence (in two phases or more). What is a challenge for the funders, though, is that the assessment criteria will have to change from one phase to the other and the level of funding is likely to escalate.

When the funders assess the management of the project, they may have to look beyond the usual academic and administrative credentials. Experience from collaborations with stakeholders is probably the number one criterion that is to be rewarded. This is also particularly relevant when the research is not headed by a scientific institution but run from a societal body such as an NGO. Again, the assessment will heavily rely on qualitative judgements, in particular judgement about personal (communicative and others) qualities that indicate smooth and inclusive leadership also when conflicts may arise.

In general, the funders will need to be more concerned about process and integrative networking, than about academic outputs such as publications. Thus, when they assess the grant, they must consider a number of questions

Assessing the Proposal: Considerations for the Assessment Panel

- Does the application suggest an understanding of the need to explore the issues which may be far deeper than simply improving water quality (which is a proxy measure for enhancing the state of the whole human and environmental ecosystem of Newar State and City)? Do the applicants acknowledge these much broader dimensions?
- Does the application show an appreciation of the full range of stakeholders who need to be employed? Has an initial stakeholder analysis been conducted? Have stakeholders been engaged in the proposal development stage?
- Does the proposal have a step of inclusive co-design recognizing that the research questions will evolve during that process or have the investigators already predefined the research questions?
- Does the proposal show a willingness for the research team to evolve, and plan iterative engagement with other stakeholders? Are non-academic stakeholders part of the team and of the research governance? How have they been selected?
- Does the proposal acknowledge the time necessary to complete the first co-design phase and for it to remain fluid and iterative?
- What is the process for agreeing and finalizing empirical steps in the process? How will stakeholders be involved? How will the data be analysed and by whom? Will stakeholders be engaged in this step?
- Does the proposal allow for adaptive protocols in response to initial findings?
- What is the range of outputs envisaged? Will all data be held and provided within the Open Science framework? Who will own the data? How will stakeholders be involved? How will the policy community be involved? What will be measured to show impact?

An Analysis of the Issues Raised

Reading through the above considerations, one thing becomes very clear: these assessments go far beyond what (academic) assessment teams are used to doing. They also go beyond the established funding schemes of most research councils and other funders. Furthermore, running such a project may go well beyond the administrative and managerial capacities of most established universities (though a project like this may be run from a unit outside academia). And, finally, the question arises: have we trained individuals to work in such a new operational space, and how do we find them?

It should be clear that the example calls for a transdisciplinary project design, one that addresses a problem field which is inherently complex, multi-factorial and interlinks different systems horizontally and vertically (a panarchy of nested systems) both natural and socio-cultural (including socio-economical) systems. Considering the post-normal framework talked about earlier, we can see that our problems with the proposal relate to the overall quality assessment. This overarching quality assessment encompasses many more factors than traditional academic peer review (cf. Pohl et al., 2011; Moser, 2016). This is also why academic publications as output are probably among the least important indicators of project quality. The funder would need to consider whether its processes are fit to assess such applications.

Let us comment on some of the questions in more detail.

Does the application suggest an understanding of the need to explore the issues which may be far deeper than simply improving water quality (which is a proxy measure for enhancing the state of the whole human and environmental ecosystem of Newar State and City)? Do the applicants acknowledge these much broader dimensions?

From the description of the issue given above, we quickly understand that any application which sets up water quality as the sole or most important overarching issue has misunderstood the broader dimensions of the case. Water may be the indicator, but only within a given context. We would look for expertise from various fields here, ecology and hydrology are certainly among them, but also agriculture, forestry and fisheries. We would like to learn more about local history. We would want to hear from a lawyer about rights and responsibilities of river uses, perhaps supplemented by an ethicist. There might be a local anthropologist who can inform us about cultural identities in the population and any relevant knowledge held in the stories and literature of the hill culture. And somebody from the paper and pulp industry could give both an environmental / ecological and economic perspective. Last, but certainly not least, we would like to hear the 'real politics' from those involved in and maybe also studying the political processes in the area.

Now, it is important for effective transdisciplinary activity that we go beyond merely having these diverse groups and expertise all lined up. The specific research questions can only be developed *after* the first phase of the project has been conducted in consultation with the stakeholders. We must put together these groups and come to a common understanding of the specific problems we need to research and learn more about. The danger of going in too early with predefined problem formulations is that the problems will precisely mirror the disciplinary perspectives of the academic researchers, rather than the problems as perceived by the diverse stakeholders. The best research is of no use if it addresses the wrong problems. This process must be reflected in the proposal, as the first task of project development. Designing the research protocols in transdisciplinary projects is never the first step and is only a part of an iterative process, negotiated with other partners and stakeholders. It should probably be assessed by a mixed group of people with experience of these kinds of projects.

Does the application show an appreciation of the full range of stakeholders who need to be employed? Has an initial stakeholder analysis been conducted? Have stakeholders been engaged in the proposal development stage?

We have already indicated the wide range of perspectives that the proposal needs to employ. It is important to recognize, and indeed stress, that expertise is included from all fields of knowledge, not only academic disciplines. Stakeholders are dialogue partners, but in transdisciplinary research they typically are partners in the research process as well, supplying their professional or traditional knowledge as input in the project. In the example above, one would expect that there is a very wide range of stakeholder knowledge to be drawn on. The oyster farmers and fishers may contribute substantially on the causes and effects of the algal blooms that hit the river earlier, to mention but one example. Not including their knowledge would effectively leave out important aspects of the problem and diminish the public trust in the project. In the long run, only the active inclusion of all relevant stakeholders can provide a robust output. This is what is commonly referred to as *co-construction* of project design and output. It will also instantiate an amplified version of *citizen science*, one where citizens are both the source of the data and active producers and providers of relevant knowledge.

Does the proposal have a step of inclusive co-design recognizing that the research questions will evolve during that process or have the investigators already predefined the research questions?

Co-design is synonymous with co-construction, and we have already commented on this question above. However, the research questions need to *evolve* in the process of co-design. Fixing the research questions too early is counter-productive in transdisciplinary projects.

Does the proposal show a willingness for the research team to evolve, and plan iterative engagement with other stakeholders? Are non-academic stakeholders part of the team and of the research governance? How have they been selected?

There are two distinct tasks alluded to in this question: the first is about governance of the research, and the second is about selection of partners and stakeholders. The governance issue raises a conundrum: the example we talk about would need a relatively large project team, with many active contributors and even more stakeholder consultants. It would run over several years and it would need quite substantial funding. All of this requires strong and competent project leadership. On the other hand, the dialogical partnership which is the backbone of any transdisciplinary project points us to collaborative bottom-up decision-making by the partners.

It is not unusual for transdisciplinary projects to be faced with seemingly contradictory objectives. The governance issue, however, need not be an either or question. Obviously, given the large group of people involved, the long timespan and the amount of funding, we need a strong management component. But this strong leadership need not encompass complete control over the substantial issues of how to approach the issues or what issues to approach in the first place. These can be left to what is effectively the 'General Assembly/Plenary Consortium' of the project. This management structure should be assisted by an Ethics Advisory Board and an agreed process to address conflicts should they arise.

The selection of the participating stakeholders is the second issue within the question. We would aim for stakeholders who can be partners in the co-governance of the project, and who also are among the affected parties. A preliminary analysis of possible stakeholders and their representatives should precede any decision on this matter. However, not all stakeholders will be represented through an organized group. Some may simply be scattered individuals, while others may be organized in different and competing NGOs or be subsumed into larger social structures (churches, etc.). The task in a transdisciplinary project is to achieve a balance of voices that together exhaust the space of relevant knowledge and relevant value-landscapes. At the same time, we need stakeholders who enter the project collaboration with an open mind in the spirit of constructive dialogue. Groups or representatives who mainly seek publicity or a channel to voice their preconceived programmes or ideas are usually not good partners.

All this requires the judgement, experience and independence/neutrality of those who select the stakeholders, but even more so of those who assess the stakeholder selection. Generally, an all-academic grouping to assess these questions would not be a good solution. Academic judgement needs to be supplemented by those with broad experience in assessment, and who have practiced independence and neutrality for some time

What is the process for agreeing and finalizing empirical steps in the process. How will stakeholders be involved? How will the data be analysed and by whom? Will stakeholders be engaged in this step?

While it may be common for stakeholders to supply data, for example in citizen science, transdisciplinary research seeks to activate stakeholders across the whole research process. Data which originate from within the stakeholders' spheres of experience will then also be analysed with the active participation of stakeholders. In our example, farmers could be actively involved in analysing the sources of pollution in the river, and fishers might help analyse catch data. Professional expertise and tacit knowledge might, in these cases, add perspectives to the analyses that escape academic perspectives.

Does the funding model and the proposal acknowledge the time necessary to complete the first co-design phase and for it to remain fluid and iterative?

The time dimension is naturally problematic for projects such as the one described here. Consultation takes time and cannot be tokenistic. When projects involve many partners, the costs of running them can easily reach very large sums. The question is whether one can assess the needed time (and scope) right from the start, from the date when the proposal is submitted. We would suggest that many transdisciplinary projects need a cascading life cycle because of the inherent uncertainties following the knowledge production. The first phase of the funding would cover the initial definition of the problems and some initial data collection. Once this is done and good results are achieved, we can move to the second phase where models for interacting systems are produced, and instrumental questions are explored. Here we try to set goals for the whole research process and design possible scenarios/options for action. (In Ortwin Renn's 2021 model this would be the goal-oriented module.) Once this is done we move to the subsequent phases of the project, including data collection, empirical study and analysis. Then comes the realization of the transformative potential which must be the primary overall goal of the project, if successful. The project moves beyond the bounds of the participants and reaches out to platforms, for example, decision-makers and networks, with the intention of starting the social processes that could lead out of the original conundrum and improve the situation for the actors involved.

Does the proposal allow for adaptive protocols in response to initial findings?

Complex problem situations call for interventions and measures that cannot be precisely predicted for all possible situations. Similarly, the protocols for the planned research need to be flexible and adaptive, as does the division into different (funding) phases of the proposal. As we indicated earlier, *collaborative adaptive management* is one of the tools that is close to the ideas of transdisciplinarity.

What is the range of outputs envisaged? Will all data be held and provided within the Open Science framework? Who will own the data? How will stakeholders be involved? How will the policy community be involved? What will be measured to show impact?

Transdisciplinarity aims at *actionable knowledge*, knowledge that has the potential to make a difference in society. Given that this is the overarching criterion for quality assessment of transdisciplinary research, it follows that publication in academic peer-reviewed journals is of lesser importance than in ordinary research assessments. The crucial question to ask in the assessment is whether the output of the project reaches the relevant stakeholders and decision-makers in a form that optimizes the uptake of the information and is of a quality that is recognized by stakeholders and decision-makers as highly relevant for further development. Impact of the output is thus not what *in fact* is done as a consequence of the transdisciplinary research, but rather how the project information has been *used in preparing* the decisions for follow-up actions.

The issue of open data, while clearly the desired goal, will often face barriers. Stakeholders may have commercial data, Indigenous cultures may demand data sovereignty, politicians may have views on the risks of open data sharing, and other practical and conceptual issues can emerge. These issues must be resolved in the initial stages of the project but trust between players is needed before the discussion can proceed to a conclusion. The lead investigators and stakeholders must demonstrate how they can resolve these issues.

CONSIDERATIONS FOR THE ACADEMIC INSTITUTIONAL PARTNER

Universities and research institutes are essential partners in transdisciplinary research projects. Further they are the employers of the academics involved and the academics themselves may face issues in their career evaluation and development. Universities spend much effort in building their reputation and income by focusing on their staff's performance and creating incentives to match their interests. Generally, this is based on an assessment of academic outputs and in science this is generally in the form of publications. In turn this forms the basis of how universities are ranked and develop their reputations. Staff performance is often metricized and determines hiring, tenure and promotion. Academia and publicly funded research staff understandably therefore focus on their outputs. While performance measures are relatively well developed within institutions, institutions generally need to develop new ways to assess transdisciplinary performance if it is to thrive and their staff are to feel appropriately supported.

Systems of training, reward and funding (internal and external to the university) work against transdisciplinarity. In part, this is a fault of university organization, their often-siloed nature, and internal incentives; in part it is created by the way the funders of universities operate: but that will not change unless academia takes the lead and demonstrates what it can do. Currently, universities, funders and government often reinforce each other in a reductionist and compartmentalized approach. However, at least in Europe, where philanthropy is more available, means to develop such approaches are slowly emerging (cf. Hirsch Hadorn, 2011; Philipp et al., 2022; Duralla et al., 2022). The move away from bibliometrics as a means of assessing individual academics is gathering momentum and is to be welcomed.

The public policy community has increasingly framed universities primarily as centres of vocational training and sources of innovation, neglecting the cultural work and the broader societal function of the traditional Humboldtian university model. Consequently, the case for continued growth of public investment in universities as broad knowledge engines has become more difficult to make. Indeed, within this 'new public management' framing, universities have become even more discipline oriented and granular in their training and outputs. This trend is not conducive to transdisciplinary training or the production of actionable knowledge: 'Neoliberalism and models of higher education that are said to treat universities more like corporate organizations have become more the norm … Such trends not only encourage specialization and compartmentalization but have posed challenges to developing a view of higher education in terms of lifelong learning, student agency, and education has shifted from a public good to a private good' (Budwig and Alexander, 2020, p.6). Thus, we need to ask some critical questions about staff performance management.

Central to this is the question of whether the institution developed a clear policy for assessing academic activity of this nature? The traditional dual assessment approach based on formal academic products and teaching needs to be amended to allow for equitable recognition of transdisciplinary activity which may be reflected in community engagement in many ways. But it has proved hard for many institutions to shift away from traditional output measures in performance assessment.

These issues directly translate to the question of whether institutions acknowledge in their tenure and promotion criteria the range of non-traditional outputs and activities that we have discussed. Most of academia is weighed down by an overreliance on bibliometric analysis. Yet much transdisciplinarity will generate actionable knowledge that need not lead to traditional academic papers and certainly not those in 'high-impact journals' even though it may have high impact in the community with which the research is engaged?

If academic institutions wish to be leaders in developing transdisciplinary research and generating actionable knowledge, they will need to create a stream of evaluation criteria that reflects the nature of the activity, including acknowledging and providing for the needed time commitment, partnership development, and multidisciplinary, stakeholder, community and policy engagement.

A further issue we discuss below is how they (and indeed other institutions of the science system, including academies) can encourage and recognise early career fellows who focus on transdisciplinary activity.

ASSESSMENT OF OUTPUTS AND IMPACT

Funders and researcher employers both need tools to evaluate the quality of outputs and the impact of specific transdisciplinary research projects. Many of the issues are discussed above. Performance assessment cannot follow a simple template but must be context-specific to the class of problems being addressed. The types of questions that arise may need to be negotiated *ab initio* with the investigators and include:

- What stakeholder communication has been followed?
- Who controls the data that are generated?
- Are policy reports being produced?
- What part of the study is in the public domain?
- Are there academic papers detailing not just the results but the process? Who are the authors?
- How has the question evolved over the course of the project?
- How do different stakeholders view/assess the project?
- Has the project led to stakeholder acceptance of possible solutions?
- Has it led the policy community to more nuanced or different choices?
- Has the nature of public discourse changed?
- Is there evidence of ongoing partnerships between stakeholders and academia?

TRAINING FOR TRANSDISCIPLINARITY

What Could Universities Do?

First, universities must look to their own management systems and stop misusing metrics and structures that discourage transdisciplinary research and other forms of cross-disciplinary activity. In Europe, it may be useful to recall the five core competencies of higher education, also called the Dublin descriptors of the Bologna process (Qualifications Framework of the European Higher Education Area 2005): knowledge and understanding, applying knowledge and understanding, making judgements, communication, learning skills (cf. Kehm 2010). As a set, these should signal some good entry points for transdisciplinary training.

Irrespective of whether a student intends on a disciplinary or broader long-term focus, undergraduate training should expose students to a broad range of epistemologies and corresponding methodologies: comparing, contrasting and critiquing these. For example, all science students require knowledge of ethics, philosophy of science and how science interrelates with society (systemically and historically). Likewise, all humanities students need to understand the processes of science, have basic science literacy, and understand some core concepts and assumptions (e.g. statistics, evolution, sustainability). One further possibility would be for students to have an opportunity to explore, in an elective course (across and within the university, possibly beyond), a problem that they regard as important and motivating, preferably in a team-based environment. The University of Bergen tries to accomplish this through the interfaculty elective undergraduate course 'Danningsemner' (comparable to the German term 'Bildung') on various themes, and via the interfaculty 2-year master programme on sustainability. Other universities such as the Leuphana University in Lüneburg, Germany, or the ETH in Zurich, Switzerland, offer similar cross-disciplinary training. The programme 'Future Africa' at the University of Pretoria aims to educate students in transdisciplinary competencies.

Resolving the balance between disciplinary and broader training is an ongoing debate in many institutions. Clearly many students will embark on careers relying on disciplinary depth, but the broader dimensions discussed above will remain of value. Some disciplinary depth is needed even by those who seek a broader-based career. The diversity of approaches emerging should itself be a point of research and evaluation.

Innovative universities taking a transdisciplinary approach would likely start taking a small cadre of high-quality students who have integrative thinking skills and training them, at the upper undergraduate level, in transdisciplinary thinking. This training would likely involve problem-based teaching and project work (Budwig and Alexander 2020).

At the graduate level, higher degrees based on transdisciplinarity should be supported. However, transdisciplinary graduate training requires university-wide centres/institutes (which are not faculty led, except perhaps for administrative organization) with transdisciplinary skills to define projects and supervisors across the university suitable to provide training. This cannot be done unless there are university-wide policies encouraging faculties to collaborate on such matters, and administrative systems including finances, designed to assist. This activity is quite distinct from that of regular postgraduate activity. Students undertaking such degrees require ongoing mentorship and coursework distinctive from that of standard PhD/Masters training. They need engagement with different types of seminars and discussion, exposure to policy-makers, exposure to post-normal-science thinking and a focus on transdisciplinary framing throughout their training. The faculty members involved must have a commitment to transdisciplinarity, as part of their own research activities. Again, this innovation requires a central unit of transdisciplinary expertise to assess quality and to work with faculty to achieve these goals. This type of committed and sustained mentorship is important in an international academic environment that still hands out rewards based on discipline-bound merit.

Transdisciplinarity is as much (if not more) about training in apprenticeship mode as it is about research. Transdisciplinary teaching is distinctive in how it is conducted, as it needs to be largely problem based. Exploiting transdisciplinarity as a research tool will not limit its impact on or disadvantage any graduate students involved.

A strategy some universities have used (e.g. University of British Columbia) is to have an internal competition for a few faculty members each year to be seconded to such a centre to gain experience in transdisciplinarity thinking and application. These are seen as highly prestigious awards. At the more advanced level, centres such as the Santa Fe Institute demonstrate the prestige that can be gained. Further evaluation of different models developed worldwide would be useful. This should, in effect, stimulate closer international cooperation across universities, sharing experiences and new ideas to foster transdisciplinarity.

Importantly, because transdisciplinarity requires different groups of academics and stakeholders, who *a priori* have different knowledge bases, language, biases, world views and framings, to come together, there is an absolute need that there be a willingness to engage in complex, difficult and challenging conversations (Gethmann et al., 2015). Respect, civility and an avoidance of exclusion of valid voices is critical. Sadly, there are trends in academia that are making this much more challenging.

HOW CAN WE IMPROVE SCIENCE POLICY AND SCIENCE-FOR-POLICY TO ACCOMMODATE TRANSDISCIPLINARITY?

The discussions above highlight the need for significant reconstruction of the management of science to promote transdisciplinary research. It likely needs somewhat different instruments to those currently well developed for mode 1 research. Indeed, trying to sustain both forms of research within a singular model of funding and assessment is almost certainly inhibiting the development of quality transdisciplinary research with its distinct characteristics.

Transdisciplinary research is the preferred method for addressing a certain class of challenges. Often these are the very issues where communities and policy-makers wish to see progress. Institutional and other major funders, such as foundations, therefore need to devise distinct to assess proposals that are mode 2 focused and ring- fence funds for such research. The questions to be assessed are not the traditional questions of hypotheses/methodologies but rather how the question and project will be co-designed and developed, how stakeholders will be engaged, acknowledging that research specifics emerge during the period of grant support and considering increased funding needs may evolve. They should also consider how they will assess the quality of the products of their investment, given that traditional academic products are not the most relevant for assessing research quality.

Universities that employ researchers with engagement in transdisciplinary research need to consider human resources (HR) policies related to workload, tenure and promotion, recognizing that the impact of these researchers will not be well reflected in traditional bibliometric-based promotion criteria. They may need to appoint staff who would not meet traditional academic criteria yet are critical to making progress. They recognize the time commitment needed for good co-design, and the quality of stakeholder engagement and non-traditional outputs. How will they assess the quality and impact of the research undertaken? Whom should they consult? Few universities have considered these realities, which will ultimately determine whether academics will engage seriously and in a committed way with transdisciplinary research. They must also consider how to select postgraduate students for apprenticeship-like exposure, irrespective of their base discipline. Other actors in the academic endeavour, such as scientific academies and award committees, also need to consider their approach to evaluating transdisciplinary research and its actors.

EPILOGUE

Since the dawn of human existence, a feature of our humanity has been that we want to know the world around and within us, and understand the phenomena that we observe. Humans have found many ways to address these desires. Over the last 500 years, modern science has emerged as a way of knowing, with distinct characteristics that sought to explain what was observed through empirical data and adaptive critique without reference to belief, tradition or higher powers.

The evolution of modern science is undoubtably critical to understanding our world. It is socially organized as an institutionalized form of praxis where publicly available knowledge claims are scrutinized by peers and critically tested against empirical phenomena. The claims are derived from a multiplicity of methods largely designed to reduce bias and seek rational explanations and understandings of the world. In this form, modern science has made enormous contributions to our understanding of our health, environment, biology, and natural and social phenomena. Its utility appears in every aspect of our individual and social existence.

Science has many methodological approaches that span a broad range of disciplines. Institutions of science are well developed in high income countries but, in some ways, also constrain science through their expectations on what is fundable, who conducts it and how it is conducted. As a result, while the very idea of science is defined by normative principles, our science systems need to be much more cognizant of the context in which they operate such that they may not be unnecessarily homogenized. For much of science this works well, but there is a growing recognition that science's ability to contribute optimally to complex wicked problems, such as those within the sustainability sector, or address societal polarization is impaired. These issues involve many more actors than scientists alone and they involve access to forms of knowledge that science may not have. Existing incentives in the science system largely promote narrow disciplinary science. But this paper has argued that science can offer so much more, if it is not afraid to interact with other knowledge systems and a wide landscape of societal values. This does not and must not mean that science should compromise its principles – far from it. But while science provides a critical way of knowing, there are many situations where other forms of knowledge can add value, particularly at the local level.

Transdisciplinarity is an approach that enables science and other knowledge systems to interact in a constructive way. Its strength is, firstly, its inclusion of stakeholders from the beginning to help define the question and, secondly, the avoidance of hubris as to which knowledge systems count. It provides a way to dissect complex wicked problems in a potentially actionable manner. It does not replace normal science which continues to be critical for addressing so many issues and for driving innovation in health, environmental management and socio-economic development. But it is an approach that can address complex wicked problems where other scientific or political approaches will struggle.

Yet, transdisciplinarity is not yet sitting well within the mainstream institutions that define modern science systems – their funding mechanisms, universities as employers and assessment of academics as actors. New institutional arrangements are needed if it is to meet its promise – as well as separate funding assessment tools, acceptance that timelines and outputs are different, and that the performance of actors thus needs to be considered differently.

Our argument is not to scrap reductionist approaches and the disciplinary excellence we have built up over the years, as these are still critically important. Nor is it to compromise our understanding of what science is as a global knowledge system of immense value. Nor is it to homogenize it and claim identity with other knowledge systems with their own distinctive characteristics. Rather we propose complementing disciplinary and interdisciplinary science with innovative efforts to constructively interact with real societal problems in the company of diverse knowledge holders and stakeholders. When things get complex (which they almost always are in the real world), we see no other choice but to engage in this new effort to construct useful knowledge for understanding and management by exploring all aspects of the problem and recognizing all knowledge inputs and epistemic traditions. Doing so is more likely to lead to actionable knowledge having an effect. This is what transdisciplinarity is about, at least as we understand it.

APPENDIX 1: THEORETICAL PERSPECTIVES

Several process-oriented guides to transdisciplinary research have been published by STS scholars. We have selected three of out of many (e.g. Bergmann et al., 2012, Defila and Di Giulio, 2015, and other references in main text) to illustrate the processes. The selection may seem arbitrary, but our aim is illustrative of conceptual considerations.

1) Jahn et al. (2012) highlight how 'inner-scientific' approaches to given issues might be different from what they call a 'life-world approach' where society seeks out practical but scientifically informed solutions to its recognized problems. They describe 'problem-transformation' as one of the most crucial processes that links external societal approaches with the internal inner-scientific approaches. The linking comprises two steps. First, transforming a societal problem into a 'boundary object' enabling cooperation between a heterogeneous group of actors. Boundary objects 'are open and flexible enough to accommodate individual perspectives and meanings while at the same time maintaining an identity that is recognized by all parties involved' (ibid., p.5). From this step of broad participation and mutual recognition of the relevant boundary object, we move to the second step of the production of new knowledge. Here we may follow up with work in specialized sub-teams, typically including extra-scientific actors. The resulting interdisciplinarity is science driven, fueling a progression towards new knowledge. The third phase in the conceptual model is characterized as the assessment phase where we ask for possible contributions to both societal and scientific progress. The partnership engages in dialogues that scrutinize different epistemological perspectives seeking a second-order integration that makes them better fit-for-purpose for both societal and scientific actors. The final task is then the intervention in both societal and scientific discourses. From this, new transdisciplinary research may evolve.

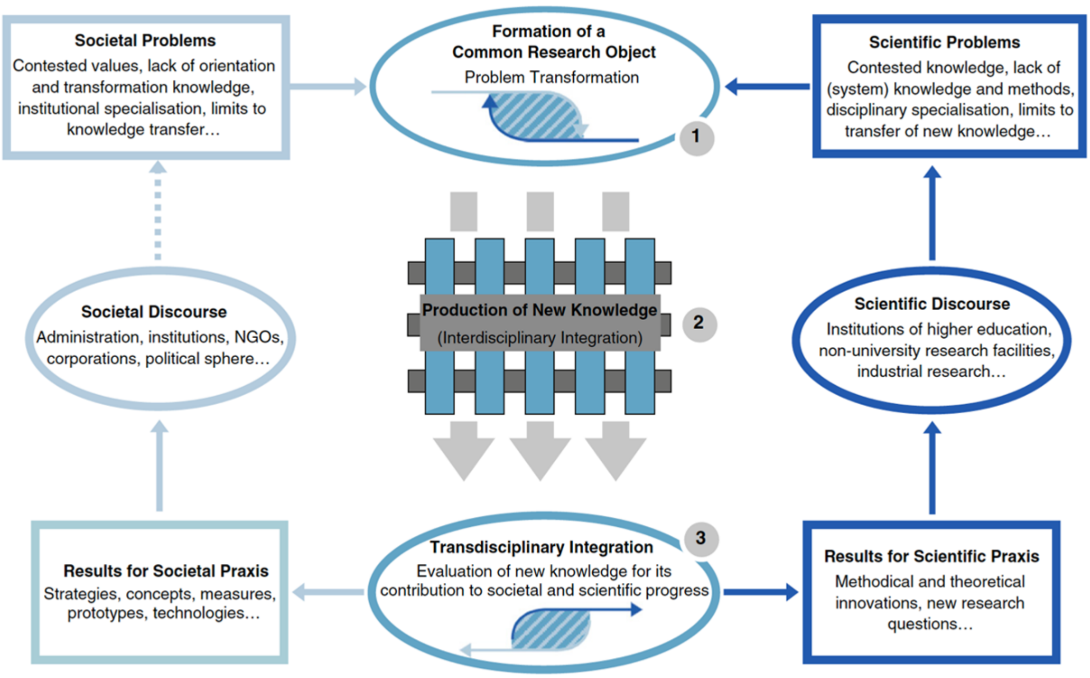

Figure A.2.

Source: Jahn et al. (2012): 'Typology of problems acording to the strength of agreement on knowledge and values.'

The authors suggest that transdisciplinarity aims to produce three types of knowledge: 'the knowledge involved in the understanding of an issue (system knowledge), that required for determining the possibilities and boundaries of decision-making (orientation knowledge), and knowledge of the ways and means of practically realizing such decisions (transformation knowledge)' (ibid., p. 8). Depending on the possible agreements or disagreements on knowledge and on values, four types of outcomes are demanded. Note that what we called 'complex wicked problems' is basically depicted as the case when agreement on knowledge and on values is low.

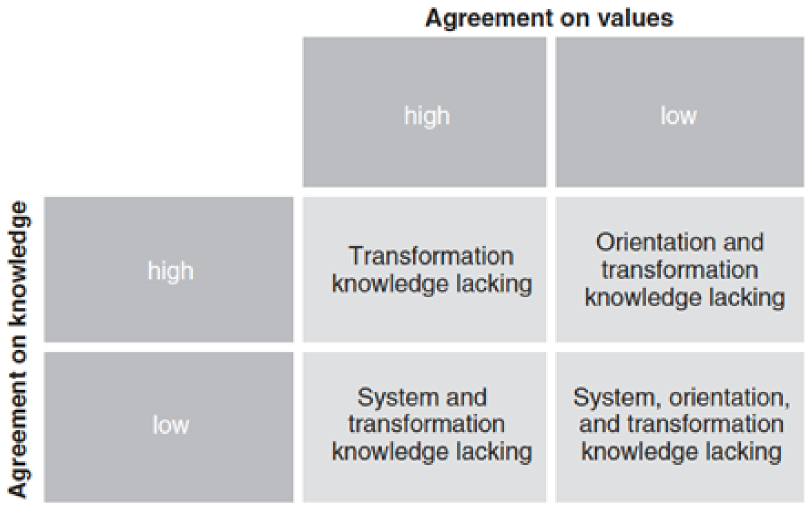

Figure A.1.

Source: Jahn et al. (2012): 'A conceptual model of transdisciplinarity. The numbers indicate the three phases of the ideal transdisciplinary research process.'

2) Largely in agreement with the model provided by Jahn et al. (2012), Renn (2021) extends the analysis by propagating a modular model. Renn's particular concern is that an appeal to increased reflexivity in transdisciplinary research does not necessarily resolve basic conflicts within either the knowledge or value orientation. There are potential conflicts between epistemic and democratic ideals when scientific knowledge is expected to be both reliable (socially robust) and (internally) justifiable. Critics maintain that this implies a problematic shift in the role of scientists from analysis to intervention, thus by extension a move from curiosity driven research to advocacy for a cause. Impartiality in the search for knowledge may collide with the overall normative orientation (e.g. sustainability) and thus promote wishful thinking, and in effect undermine trust in science as an impartial broker. Renn sees a major difficulty here: 'The clash of different rationalities between scientific and political thinking cannot be overcome by initiating a common discourse among all parties and hope for the integrative power of reflexivity as a panacea for resolving conflicts ... Truth claims, values, interests and preferences are all intertwined but they cannot be integrated into a single unity' (ibid., p. 130). Thus, for Renn, integration remains an unresolved problem, and he therefore opts for a modular approach.

Renn identifies three research traditions. The first, curiosity driven research, aims to 'find valid insights into as yet unknown connections between phenomena or dynamic developments' (ibid., p. 20), normally in the form of causal or functional relationships, driven by curiosity. Enlightening others about these insights should not be portrayed as 'ivory tower thinking' or signify academic 'siloes' but rather as corrective to 'wishful thinking and ideological blinkers'. When dealing with inherently complex issues, curiosity driven research, by necessity, goes beyond single disciplines and seeks interdisciplinarity providing system knowledge. However, curiosity driven research encounters challenges when meeting unfavourable contextual conditions in the real world.

This then promotes what Renn calls 'goal-oriented research', similar to mission-oriented research or advocacy science. Here the division between basic and applied science is dissolved, seeking to acquire knowledge towards a specific benefit, and it aims for outcomes that policy-makers can utilize to solve problems or achieve goals. Importantly, it links the present with the future. Targets are external and highly value based, either serving the public at large or serving interests and goals of specific groups. The dominance of value-based approaches here contradicts curiosity driven research. Problems with goal-oriented research stem from the fact that 'the research team is tied into a predetermined corset of objectives' (ibid., p.10). It does not question alternatives outside the given objectives and may ignore options which – judged more holistically – would implement the driving intentions better.

Renn thus moves on to describe what he calls 'catalytic research' (and others sometimes described as participatory, deliberative or reflective). This form integrates other forms of knowledge that may be useful for dealing with the problem at hand. Here is transdisciplinarity: systematically collected knowledge is transformed into a new format which is understandable and comprehensible for all partners, opening the path for a constructive dialogue about essential values among the various value-landscapes. Given the nature of complex wicked problems there is hardly ever a single overriding solution, but merely a spectrum of options. In this way, science can fulfil the role of an 'honest broker' in the shaping of policies. 'Catalytic knowledge … is aimed at finding out how to design and implement processes for evidence-informed and value-responsive discourses with a democratic institutional structure' (ibid., p.13).

These forms of research and knowledge developments overlap at some points but are not functionally equivalent, and in Renn's conception they can function as modules of a comprehensive transdisciplinary understanding of science, with each element being constitutive for a transdisciplinary nexus between science, society and politics.

Three concepts of scientific research for policymaking purposes.

Concept	Curiosity-driven	Goal oriented	Catalytic
Knowledge Type	systematic	instrumental	processual
Function for policymaking	orientation (enlightenment)	problem solving	co-creation
Forms of expression	analyses (causal/functional)	scenarios/options	process architecture
Limits and problems	coping with complexity	goal fixation	Lack of universality

Figure A.3. Characteristics of three modes of scientific research

Source: Renn (2021)

3) Carew and Wickson (2010) offer what they call an adaptable heuristic in the form of a transdisciplinary wheel. They base this tool on the observation that transdisciplinary research needs to go through three formative phases: *shaping* which consists of planning and proposing the research, *supporting* consists of guiding the research in process, and *evaluating* consists of planning for evaluation, periodically documenting progress and reporting of the outcomes. They identify one of the major hurdles in transdisciplinary research as *context* identification to which the research needs to be responsive. Thus, process, product and context represent special challenges for transdisciplinary research but provide a way ahead that would be difficult to surmount with more traditional disciplinary or even interdisciplinary approaches.

The context comprises the problem context (e.g. the level of uncertainty, the degree of contestation and decision stakes, the extent of agency, etc.), the research context (e.g. the available funding mechanisms, the opportunity for formal and informal face-to-face consultations among partners, existing power relations at the research institution, etc.), and the researcher's context (e.g. past experience, the skills of moderation and integration, inclination to interact with different epistemologies and values, willingness to engage in reflexivity and account for own bias, etc.). All these factors might influence the design of the project. They cite Funtowicz and Ravetz (1993) and their point of iteratively using extended peer review is particularly salient.

However, in this kind of research the process needs to be adaptable to challenges that appear only after the start of the project. 'Transdisciplinary research processes are enacted within real-world contexts that may distort actions in unforeseen or unintended ways' (ibid., p.1152). This will in turn affect the planned outcome of the project.

The third element, product, comprises a range of types of outcomes and impact discussed in the literature. Carew and Wickson operate here with three distinctive challenges for quality assessment: peer approval, problem solving and mutual learning. Obviously, the first one, peer approval, is bound to face difficulties when subjected to the 'scrutiny from multiple peer communities associated with the research problem and its context' (ibid., p.1152). The problem-solving contribution of the research is likewise not easily assessed. Is it the actual implementation of suggested policies, or a shift in the public discourse? And how long do we need to wait until such changes can be recorded? The assessment should most probably involve those who are affected by the problem. The third type of outcome can be mutual learning taking place among all the partners in the project. The difficulty is typically to agree on standards for how to assess this learning over the life of the research project.

The authors stress the dynamic and non-linear relationship among these elements during a transdisciplinary research project. Interactions and movements will occur at various stages and with various actors. The dynamic pictorial representation of their transdisciplinary wheel looks like this.

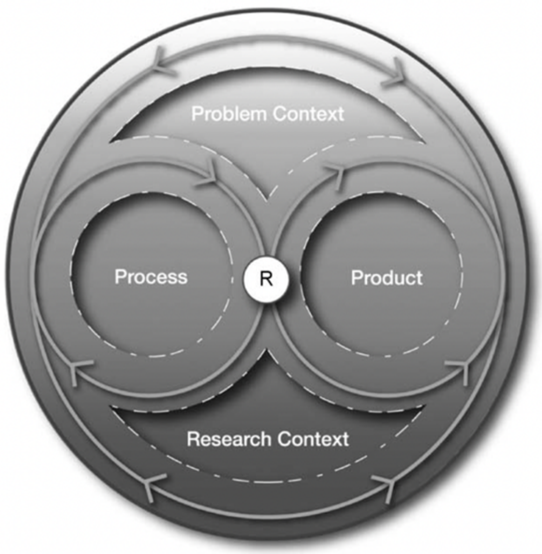

Figure A.4.

Source: Carew and Wickson(2010): 'The Transdisciplinary Wheel in motion'

Carew and Wickson specify this dynamic with four 'traces', each depicting different interactions at different stages during the process. For instance, trace C 'shows researcher/s cycling between process and product, without substantial engagement in context' (ibid., p.1154), while trace B depicts a negotiation between researchers and the research context and trace D shows the more mature state of the project.

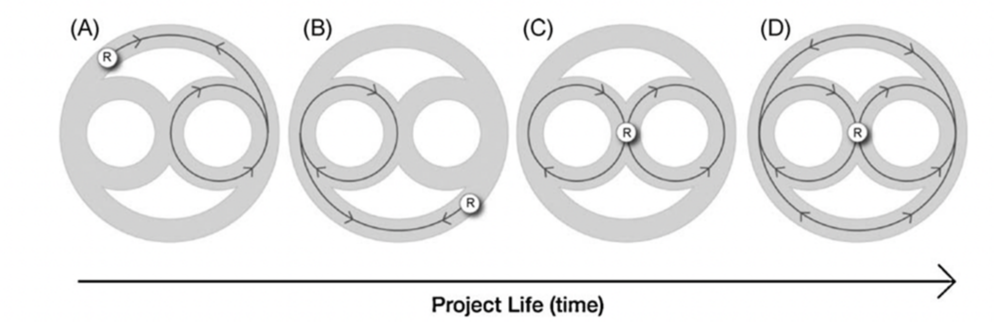

Figure A.5.

Source: Carew and Wickson, (2010, p.1154): 'Traces of the Transdisciplinary Wheel in application'

REFERENCES

Anthony-Stevens, V. and Matsaw Jr, S. L. 2020. 'The productive uncertainty of Indigenous and decolonizing methodologies in the preparation of interdisciplinary STEM researchers'. Cultural Studies of Science Education, Vol. 15, pp. 595–613.

Arnott, J. C., Neuenfeldt, R. J. and Lemos, M. C. 2020. 'Co-producing science for sustainability: can funding change knowledge use?'. Global Environmental Change, Vol. 60, p. 101979.

Arnstein, S. 1969. 'A ladder of citizen participation'. Journal of the American Planning Association, Vol. 35, No. 4, pp. 216–24.

Barreteau, O., Bots, P. W. and Daniell, K. A. 2010. 'A framework for clarifying "participation" in participatory research to prevent its rejection for the wrong reasons'. Ecology and Society, Vol. 15, No. 2.

Benessia, A. and De Marchi, B. 2017. 'When the earth shakes... and science with it. The management and communication of uncertainty in the L'Aquila earthquake'. Futures, Vol. 91, pp. 35–45.

Belcher, B. M., Rasmussen, K. E., Kemshaw, M. R. and Zornes, D. A. 2016. 'Defining and assessing research quality in a transdisciplinary context'. Research Evaluation, Vol. 25, No. 1, 1–17.

Bergmann, M., Jahn, T., Knobloch, T., Krohn, W., Pohl, C., and Schramm, E. 2012. Methods for Transdisciplinary Research: A Primer for Practice. Frankfurt, Campus Verlag.

Bernstein, J.H. 2015. 'Transdisciplinarity: A review of its origins, development, and current tissues'. Journal of Research Practice, Vol. 11, pp. 1–20.

Bieluch, K. H., Bell, K. P., Teisl, M. F., Lindenfeld, L. A., Leahy, J. and Silka, L. 2017. 'Transdisciplinary research partnerships in sustainability science: an examination of stakeholder participation preferences'. Sustainability Science, Vol. 12, pp. 87–104.

Breda, J. and Swilling, M. 2019. 'The guiding logics and principles for designing emergent transdisciplinary research processes: learning experiences and reflections from a transdisciplinary urban case study in Enkanini informal settlement, South Africa'. Sustainability Science, Vol. 14, pp. 823–41.

Brown, M. B. 2013. 'Philip Kitcher, Science in a Democratic Society'. Minerva, Vol. 51, pp 389-397

Brown, J. R. 2021. Who Rules in Science? Cambridge, MA, Harvard University Press.

Budwig, N. and Alexander, A. J. 2020. 'A transdisciplinary approach to student learning and development in university settings'. Frontiers in Psychology, Vol. 11, p. 576250.

Bush, V. 1945. 'Science, the endless frontier'. Reprint. Princeton, NJ: Princeton University Press, 2021.

Carew, A. L. and Wickson, F. 2010. 'The TD wheel: a heuristic to shape, support and evaluate transdisciplinary research'. Futures, Vol. 42, No. 1, pp. 1146–55.

Chalmers, a. F. 2013.What is This Thing Called Science? Cambridge, Hackett Publishing.

Chambers, J. M., Wyborn, C., Ryan, M. E., Reid, R. S., Riechers, M., Serban, A., ... and Pickering, T. 2021. 'Six modes of co-production for sustainability'. Nature Sustainability, Vol. 4, No. 11, pp. 983–96.

Chilisa, B. 2017. 'Decolonising transdisciplinary research approaches: an African perspective for enhancing knowledge integration in sustainability science'. Sustainability Science, Vol. 12, No. 5, pp. 813–27.

Clark, B., and Button, C. 2011. ‘Sustainability transdisciplinary education model: Interface of arts, science, and community (STEM)’. International Journal of Sustainability in Higher Education, Vol. 12, No. 1, pp. 41–54.

Cole, A. 2017. ‘Towards an Indigenous transdisciplinarity’. Transdisciplinary Journal of Engineering and Science, No. 8.

Copland, P. 2003. ‘Science and ethics must not be separated’. Nature, Vol. 425, No. 6954, p. 121.

Daston, L. 1991. ‘The ideal and reality of the republic of letters in the enlightenment’. Science in Context, Vol. 4, No. 2; pp. 367–86.

Daston, L. and Galison, P. 2010. Objectivity. Princeton, NJ, Princeton University Press.

De la Vega-Leinert, A. C. and Schönenberg, R. 2020. ‚Transdisciplinary perspectives on current transformations at extractive and agrarian, frontiers in Latin America’. Journal of Land Use Science, Vol. 15, No. 2–3, pp. 99–107.

Defila, R. and Di Giulio, A. 2015. ‘Integrating knowledge: challenges raised by the “Inventory of Synthesis”’. Futures, Vol. 65, pp. 123–35.

Deutsch, S., Keller, R., Krug, C. B. and Michel, A. H. 2023. ‘Transdisciplinary transformative change: an analysis of some best practices and barriers, and the potential of critical social science in getting us there’. Biodiversity and Conservation, 1–26.

Douglas, H. 2009. Science, Policy, and the Value-Free Ideal. Pittsburgh, PA, University of Pittsburgh Press.

Duralla, E., Carter, C. and Burns, K. 2022. ‘Transdisciplinary education and innovation through STEAM’. Proceedings of the Mini-Conference on Transdisciplinary Research and Design (TraD).

Funtowicz, S. O. and Ravetz, J. R. 1990. Uncertainty and Quality in Science for Policy (Vol. 15). New York, Springer.

Funtowicz, S. O. and Ravetz, J. R. 1993. ‘Science for the post-normal age’, Futures, Vol. 26, No. 6, pp. 568–82.

Gethmann, C.F., Carrier, M., Hanekamp, G., Kaiser, M., Kamp, G., Lingner, S., Quante, M. and Thiele, F. 2015. Interdisciplinary Research and Trans-disciplinary Validity Claims. Heidelberg, Springer.

Gibbons, M., Limoges, C., Scott, P., Schwartzman, S. and Nowotny, H., 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. London, Sage Publications.

Giere, Ronald N. ; Bickle, John and Mauldin, Robert F. 1991. Understanding Scientific Reasoning. Fort Worth, TX, Wadsworth Publishing Company.

Giere, R. N. 2010. Scientific Perspectivism. Chicago, IL, University of Chicago Press.

Gigerenzer, G. 2008. ‘Why heuristics work’. Perspectives on Psychological Science, Vol. 3, No. 1, pp. 20–9.

Gluckman, P. and Hanson, M. 2019. Ingenious: The Unintended Consequences of Human Innovation. Cambridge, MA, Harvard University Press.

Gooding, H., Lattanzio, S., Parry, G., Newnes, L., and Alpay, E. 2023. ‘Characterising the transdisciplinary research approach’. Product: Management and Development, Vol. 20, No. 2.

Hacking, I. 1983. Representing and Intervening: Introductory Topics in the Philosophy of Natural

Science. Cambridge, Cambridge University Press.

Hadorn, G. H., Hoffmann-Riem, H., Biber-Klemm, S., Grossenbacher-Mansuy, W., Joye, D., Pohl, C., ... and Zemp, E. (Eds.). 2008. Handbook of Transdisciplinary Research (Vol. 10). Dordrecht, The Netherlands, Springer.

Henry, J. 2016. 'The Scientific Revolution: Five books about it'. Isis, Vol. 107, pp. 809–17.

Hadorn, G. H., Schmied, B. and Frischknecht, P. 2011. Transdisciplinary elements in university education: the case of the environmental science programme at ETH Zurich. La transdisciplinarité: comment explorer les nouvelles interfaces. Paris, Hermann, pp. 73–102.

International Science Council. 2021. Unleashing Science: Delivering Missions for Sustainability. Paris, International Science Council. DOI: 10.24948/2021.04.

International Science Council 2022. Global Commission on Science Missions for Sustainability: Action Plan. Paris, International Science Council. https://council.science/actionplan/funding-science-global-commission/

Jahn, T., Bergmann, M. and Keil, F. 2012. 'Transdisciplinarity: Between mainstreaming and marginalization'. Ecological Economics, Vol. 79, pp. 1–10.

Joravsky, D. 1962. 'The Lysenko Affair'. Scientific American, Vol. 207, No. 5, pp. 41–9.

Kaiser, M. 2000. Hva er vitenskap? Oslo, Universitetsforlaget.

Kaiser, M. 2022. 'Taking value-landscapes seriously'. In Transforming Food Systems: Ethics, Innovation and Responsibility. Wageningen, The Netherlands, Wageningen Academic Publishers, pp. 46–51.

Kaiser, M. in press. 'The idea of values and the metaphor of value-landscapes'. Submitted to Humanities and Social Sciences Communications.

Kahnemann, D. 2017. Thinking, Fast and Slow. New York, Farrar, Straus and Giroux.

Kehm, B. M. 2010. 'Quality in European higher education: The influence of the Bologna Process'. Change: The Magazine of Higher Learning, Vol. 42, No. 3, pp. 40–6.

Kareem, B., McClure, A., Walubwa, J., Koranteng, K., Mukwaya, P. I., and Taylor, A. 2022. 'Power dynamics in transdisciplinary research for sustainable urban transitions'. Environmental Science and Policy, Vol. 131, pp. 135–42.

Kitcher, P. 2011. Science in a Democratic Society. Amherst, Prometheus Books.

Klein, J. T. 2013. 'The transdisciplinary moment (um)'. Integral Review, Vol. 9, No. 2, pp. 189–99.

Klein, J. T. 2015. 'Reprint of "Discourses of transdisciplinarity: Looking back to the future"'. Futures, Vol. 65, pp. 10–16.

Knapp, C. N., Reid, R. S., Fernández-Giménez, M. E., Klein, J. A. and Galvin, K. A. 2019. 'Placing transdisciplinarity in context: A review of approaches to connect scholars, society and action'. Sustainability, Vol. 11 No. 18, pp. 4899.

Kuhn, T. 1962. The Structure of Scientific Revolutions. Chicago, IL, University of Chicago Press.

Leach, M. 2020. 'Echoes of Ebola: social and political warnings for the COVID-19 response in African settings'. http://somatosphere.net/forumpost/echoes-of-ebola/

Longino, H. E. 2002. 'Science and the common good: Thoughts on Philip Kitcher's Science, Truth, and Democracy'. Philosophy of Science, Vol. 69, No. 4, pp. 560–68.

Low, F. M., Gluckman, P. D. and Hanson, M. A. 2019. 'Niche modification, human cultural evolution and the Anthropocene'. Trends in Ecology and Evolution, Vol. 34, No. 10, pp. 883–85.

Lubchenco, J. 1998. 'Entering the century of the environment: A new social contract for science'. Science, Vol. 279, No. 5350, pp. 491–97.

Mach, K. J., Lemos, M. C., Meadow A. M., Wyborn, C., Klenk, N., Arnott, J. C., Ardoin, N., M., Fieseler, C., Moss, R. H., Nichols, L., Stults, M., Vaughan, C. and Wong-Parodi, G. 2020. 'Actionable knowledge and the art of engagement'. Current Opinion in Environmental Sustainability, Vol. 42, pp: 30-37.

Mapara, J. 2009. 'Indigenous knowledge systems in Zimbabwe: Juxtaposing postcolonial theory'. Journal of Pan African Studies, Vol. 3, No. 1.

Marks, J. 2009. Why I am not a Scientist. Berkeley and Los Angeles, University of California Press.

McIntyre, L. 2019t. The Scientific Attitude: Defending Science from Denial, Fraud, and Pseudoscience. Cambridge, MA, MIT Press.

Merton, R.K. 1942. 'The normative structure of science'. R. K. Merton (ed.), The Sociology of Science: Theoretical and Empirical Investigations. Chicago, IL, University of Chicago Press, pp. 1973.

Moser, S. C. 2016. 'Can science on transformation transform science? Lessons from co-design'. Current Opinion in Environmental Sustainability, Vol. 20, pp. 106–15.

Mitroff, I. I. 1974. 'Norms and counter-norms in a select group of the Apollo moon scientists: A case study of the ambivalence of scientists'. American Sociological Review, Vol. 39, pp. 579–95.

Murvold, E. H. and Kaiser, M. 2022. 'Transdiciplinarity action in Greece'. Norway, AFINO. https://www.ntnu.no/blogger/afino/2022/07/28/transdisciplinarity-in-action-in-greece/

Needham, J. 1954. 'Science and Civilization in China'. Cambridge University Press, Cambridge, UK.

Nicolescu, B. 2002. Manifesto of Transdisciplinarity. New York, SUNY Press.

Nicolescu, B. 2010. Methodology of Transdisciplinarity-Levels of Reality, Logic of the Included Middle and Complexity. The Atlas, vol. 1, pp. 17-32.

Nicolescu, B. 2014. 'Methodology of transdisciplinarity'. World Futures, Vol. 70, No. 3-4, pp. 186–99.

Niiniluoto, I. 2002. 'Scientific progress'. Stanford Encyclopedia of Philosophy.

Niiniluoto, I. 2012. Truthlikeness (Vol. 185). Dordrecht, The Netherlands, Springer Science and Business Media.

Niiniluoto, I. 2017. 'Optimistic realism about scientific progress'. Synthese, Vol. 194, No. 9, pp. 3291–309.

OECD 2020. 'Addressing societal challenges using transdisciplinary research'. STI Policy Paper. Paris, OECD.

Okasha, S. 2016. Philosophy of Science: A Very Short Introduction. Oxford, Oxford University Press, 2002.

Oreskes, N. 2015. 'How earth science has become a social science'. Historical Social Research/ Historische Sozialforschung, pp. 246–70.

Oreskes, N. 2019. Why Trust Science? Princeton, NJ, Princeton University Press.

Osborne, P. 2015. 'Problematizing disciplinarity, transdisciplinary problematics'. Theory, Culture and Society, Vol. 32, No. 5–6, pp. 3–35.

Pereira, L. M., Karpouzoglou, T., Frantzeskaki, N. and Olsson, P. 2018. 'Designing transformative spaces for sustainability in social-ecological systems'. Ecology and Society, Vol. 23, No. 4.

Philipp, T., Casiraghi, D., Enelund, M., Kubiś, M., Sancassani, S., Ruiz, L. M. S., ... and Yusim, I. 2022. Toolkit on Transdisciplinary Education and Science. ENHANCE Alliance.

Pohl, C., Perrig-Chiello, P., Butz, B., Hadorn, G. H., Joye, D., Lawrence, R., ... and Zinsstag, J. 2011. Questions to evaluate inter-and transdisciplinary research proposals. TD-NET Network for Transdisciplinary Research.

Pohl, C. 2011. What is progress in transdisciplinary research? Futures, Vol. 43, No. 6, pp. 618–26.

Pohl, C., Perrig-Chiello, P., Butz, B., Hadorn, G. H., Joye, D., Lawrence, R., ... and Zinsstag, J. 2011. 'Questions to evaluate inter-and transdisciplinary research proposals'. TD-NET Network for Transdisciplinary Research.

Popper, K. 1963. Conjectures and Refutations: The Growth of Scientific Knowledge. New York, Routledge.

Ravetz, J. R. 1971. Scientific Knowledge and its Social Problems. Oxford, Oxford University Press.

Renn, O. 2021. Transdisciplinarity: Synthesis towards a modular approach. Futures, Vol. 130, pp. 102744.

Rittel, H. W. and Webber, M. M. 1973. 'Wicked problems'. Man-made Futures, Vol. 26, No. 1, pp. 272–80.

Ross, S. 1962. 'Scientist: The story of a word'. Annals of Science, Vol. 18, No. 2, pp. 65–85.

Rudner, R. 1953. 'The scientist qua scientist makes value judgements' Philosophy of Science, Vol. 20, No. 1, pp. 1–6.

Russell, A. W., Wickson, F., and Carew, A. L. 2008. 'Transdisciplinarity: Context, contradictions and capacity'. Futures, Vol. 40, No. 5, pp. 460–472.

Ruwhiu, D., Arahanga-Doyle, H., Donaldson-Gush, R., Bragg, C., Kapa, J. and Kāti Huirapa Rūnaka ki Puketeraki. 2021. 'Enhancing the sustainability science agenda through Indigenous methodology'. Sustainability Science, Vol. 17, pp. 403–414 .

Saltelli, A., Benini, L., Funtowicz, S., Giampietro, M., Kaiser, M., Reinert, E. and van der Sluijs, J. P. 2020. 'The technique is never neutral. How methodological choices condition the generation of narratives for sustainability'. Environmental Science and Policy, Vol. 106, pp. 87–98.

Schneider, F., Tribaldos, T., Adler, C., Biggs, R. O., de Bremond, A., Buser, T., ... and Zondervan, R. 2021. 'Co-production of knowledge and sustainability transformations: a strategic compass for global research networks'. Current Opinion in Environmental Sustainability, Vol. 49, pp. 127–142.

Schneider, F., Llanque-Zonta, A., Andriamihaja, O. R., Andriatsitohaina, R. N. N., Tun, A. M., Boniface, K., ... and Zaehringer, J. G. 2022. 'How context affects transdisciplinary research: insights from Asia, Africa and Latin America'. Sustainability Science, Vol. 17, pp. 2331–45 .

Shrivastava, P., Smith, M. S., O'Brien, K., and Zsolnai, L. 2020. 'Transforming sustainability science to generate positive social and environmental change globally'. One Earth, Vol. 2 No. 4, pp. 329–40.

Simon, H. A. 1979. ‘Rational decision making in business organizations’. The American Economic Review, Vol. 69, No. 4, pp. 493–513.

Steel, B. S., Lach, D. and Weber, E. P. 2017. New Strategies for Wicked Problems: Science and Solutions in the 21st Century. Corvallis, OR, Oregon State University Press.

Stichweh, R. 1992. ‘The sociology of scientific disciplines: On the genesis and stability of the disciplinary structure of modern science’. Science in Context, Vol. 5, No. 1, pp. 3–15.

Strevens, M. 2020. The Knowledge Machine: How Irrationality Created Modern Science. New York, Liveright Publishing.

Todd, P. M. and Gigerenzer, G. 2000. ‘Précis of “Simple heuristics that make us smart”’. Behavioral and Brain Sciences, Vol. 23, No. 5, pp. 72741.

UNESCO. 2017. ‘Recommendation on Science and Scientific Researchers. Adopted under the theme of Social and Human Sciences in Paris, France, 13 November 2017’. Paris, UNESCO.

UNESCO. 2021. ‘Recommendation on Open Science. Paris, France; 9-24 November 2021’. Paris, UNESCO.

Van Kerkhoff, L. 2014. ‘Developing integrative research for sustainability science through a complexity principles-based approach’. Sustainability Science, Vol. 9, pp. 143–55.

Verwoerd, L., Klaassen, P., Van Veen, S. C., De Wildt-Liesveld, R. and Regeer, B. J. 2020. ‘Combining the roles of evaluator and facilitator: Assessing societal impacts of transdisciplinary research while building capacities to improve its quality’. Environmental Science and Policy, Vol. 103, pp. 32–40.

Weber, M. 1946. ‘Science as a vocation’. Science and the Quest for Reality. London, Palgrave Macmillan, pp. 382–94

Weinberg, A. M. 1972. ‘Science and trans-science’. Science, Vol. 177, No. 4045, p. 211.

Wickson, F., Carew, A. L., and Russell, A. W. 2006. ‘Transdisciplinary research: characteristics, quandaries and quality’. Futures, Vol. 38, No. 9, pp. 1046–59.

Wickson, F., and Carew, A. L. 2014. ‘Quality criteria and indicators for responsible research and innovation: Learning from transdisciplinarity’. Journal of Responsible Innovation, Vol. 1, No. 3, pp. 254–73.

Yıldız, D. 2019. Systems Thinking and Transdisciplinary Approach for Sustainable Groundwater Management. Water Diplomacy and Science News, Vol. 12019-10010.

Zegeye, A., and Vambe, M. 2006. ‘African Indigenous knowledge systems’. Review (Fernand Braudel Center), pp. 329–58.

Zhang, M. 2022. ‘The plurality of scientific culture and its value’. Culture of Science, 5(3) pp: 43-45.

Zurba, M. and Papadopoulos, A. 2021. ‘Indigenous participation and the incorporation of Indigenous knowledge and perspectives in global environmental governance forums: A systematic review’. Environmental Management, pp. 1–16.

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