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REVIEW ARTICLE

Process ownership in science–practice collaborations: the special role of transdisciplinary processes in sustainable transitioning

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Abstract
The complexity and importance of environmental, societal, and other challenges require new forms of science and practice collaboration. We first describe the complementarity of method-driven, theory-based, and (to the extent possible) validated scientific knowledge in contrast to real-world, action-based, and contextualized experimental knowledge. We argue that a thorough integration of these two modes of knowing is necessary for developing ground-breaking innovations and transitions for sustainable development. To reorganize types of science–practice collaborations, we extend Stokes's Pasteur's quadrant with its dimensions for the relevance of (i) (generalized) fundamental knowledge and (ii) applications when introducing (iii) process ownership, i.e., who controls the science–practice collaboration process. Process ownership is a kind of umbrella variable which comprises leadership (with the inflexion point of equal footing or co-leadership) and mutuality (this is needed for knowledge integration and developing socially robust orientations) which are unique selling points of transdisciplinarity. The extreme positions of process ownership are applied research (science takes control) and consulting (practice takes process ownership). Ideal transdisciplinary processes include authentic co-definition, co-representation, co-design, and co-leadership of science and practice. We discuss and grade fifteen approaches on science–practice collaboration along the process ownership scale and reflect on the challenges to make transdisciplinarity real.

Keywords Transdisciplinary processes · Mutual learning · Scientific relevance · Practical relevance · Process ownership · Complexity management

Introduction

Keeping planet Earth viable in the twenty-first century and beyond without disruptions calls for identifying successful coping strategies to manage current fundamental challenges including climate change, pandemic threats, international security, ensuring food security, biodiversity loss, rebound effects of new technologies, digitalization, migration, sustainable energy systems, and sustainable resource management. The need to better understand the fundamental character of interactions between nature and society and necessary adaptive capacities are central subjects of sustainability science (Clark and Harley 2020; Kates et al. 2001). The complexity, contextualization, and multifaceted nature of such problems require the utilization of knowledge and epistemics (i.e., ways of knowing) of different interest groups (including governmental actors, industry, non-profit organizations, NGOs and other stakeholders) and cultures (including indigenous people). Knowledge also differs between modes of thought (e.g., intuition vs analytics) and depends on the

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perspectives of interest (Scholz 2011). We argue that to properly utilize and develop science that can cope with these challenges, different forms of science–practice collaboration have been and continue to be developed, and this compels us to define, interrelate, and effectively use the capacities of both science and practice for linking practical experiential wisdom and academic rigor (Renn 2021). We also reflect on how science knowledge may affect the actions of decision makers.

First, to understand what determines the potential of collaboration, we define the essence of each one, scientific and practical knowledge. Simplified, science knowledge serves to construct a reference system of validated common knowledge that is (1) consistent and/or (2) empirically proven or validated. In contrast, practical knowledge serves to master life, to compete in daily life, and to secure and strengthen one's position in society. From a realist perspective, scientists construct theories and models to realistically describe structures and processes of the actual world. The objectives of practitioners differ. For example, business agents must compete and survive in the market and provide sufficient turnover and profit; politicians in democratic systems strive to be re-elected; and NGOs must find appropriate ways of gaining public acknowledgment for their values and norms.

Second, science and practice differ primarily in the criteria they use for validating what is good or successful. In a traditional conception of science, the objective is to construct theories and models approaching real structures, and the primary driver is curiosity. In contrast, practitioners' success is based on feedback from their social and natural environment that support or endanger the viability of their systems. For representatives of commercial organizations, for example, market success and economic return are decisive. For politicians and actors of nongovernmental organizations, popularity, social recognition, and the number of votes/memberships are significant. A good strategy is specific, situated (e.g., adapted to the socio-cultural constraints in contrast to generic science knowledge; Gherardi 2008; Hunter 2009), and often intuitive or implicit (Greenhalgh 2002; Raab and Gigerenzer 2015).

Third, from our perspective, collaboration goes beyond cooperation. Cooperation is directed toward the division of labor and knowledge, while collaboration stresses *mutuality*. It includes an intended joint process of creating prerequisites and constraints and framework conditions, as well as the intertwining of ideas and actions on the course toward a common goal. Thus, science–practice collaboration comprises goal-oriented interaction and knowledge integration to address a challenge or endeavour that is of interest to both practitioners and scientists. For instance, the challenge of complex, socioecological transitions calls for going beyond interdisciplinarity and utilizing the multitude of epistemics, which are related and linked to different interests of subgroups of society and their experiential foundations (wisdom), which have often been acquired by cultural rationales.

The aim of transdisciplinary processes is to provide added value for science and practice through the effective, functional integration of knowledge from both. The integration of knowledge from science and practice provides a special form of epistemics, but also the integration of sciences for a targeted interdisciplinarity is part of (i) epistemic integration. Further, a transdisciplinary project is characterized by integration of (ii) systems, (iii) interest groups/social interest, (iv) modes of thought, and (v) cultures (Scholz 2011; Scholz and Steiner 2015b). All these forms serve capacity building of all stakeholder groups by mutual learning on equal footing/co-leadership of science and practice is our understanding—and thus may serve as a short definition—of transdisciplinary processes.

In this paper, we describe different types of science–practice collaboration and discuss when, how, and why transdisciplinary processes may complement other established approaches such as political consultancy, Triple Helix, Third Mission, open innovation, citizen science, and action research. We do this from a systemic sustainability perspective. Sustainable development is seen (Scholz 2017) as:

1. an ongoing search for and inquiry about problems and critical environmental dynamics that
2. identify and assess critical risks and vulnerabilities for the maintenance of (sub-)systems considered essential for the viability of humankind or those systems that are judged valuable to maintain
3. from a socio-cultural normative perspective such as intra- and intergenerative justice.

The number and extent of contributions from science and practice differ along three stages. The ongoing search for threats (1) may be viewed as a joint process. Thus, practitioners might take the lead on problems that require experiential knowledge, while scientists take it in domains where abstract knowledge is required, e.g., long-term climate change. In the course of assessing vulnerabilities and resilience, science is likely to take the lead, while the formation of normative goals and objectives to address the results of their assessments is usually considered a matter for societal democratic processes (Scholz 2017).

We argue that scientists and practitioners have different reference, reward, and validation systems, yet there is heterogeneity within and between science and practice as well. Scientists may see themselves and their role as serving the public good, which aligns with the fact that, in many countries, it is taxpayers who finance public science institutions. Nevertheless, there is an ongoing discussion of the role of science activists (or lobbyists in "the coat of science"), e.g., when defining goals for climate protection, the risks society should take, or what constitutes sustainable consumption (Scholz 2017; Wittmayer 2016). The presented approach of transdisciplinarity stresses that the normative side of coping with a transdisciplinary problem is a primary subject of practice/stakeholders and not of science (Scholz 2020).

"Science vs practice: who is generating what type of knowledge?" first describes what knowledge is generated by science and what by practice. We delineate how transdisciplinarity differs from societal and business-driven Third Mission research and explain the complementarity of science and practice with respect to rationales and drivers. Then, we outline motives and rationales for why scientists and practitioners collaborate. "Process ownership in science–practice collaborations" introduces the process ownership scale which provides a third dimension to Pasteur's quadrant (Stokes 1997) by differentiating constellations of leadership by science or practice. The "Discussion", and "Conclusions and outlook" focus on the motivations and drivers of both science and practice actors and elaborate on the reasons of why transdisciplinary processes are appropriate for sustainable transitions, based, in particular, on equal process ownership and mutual learning for capacity building of science and practice.

Science vs practice: who generates what type of knowledge?

The bifurcation of the Third Mission vs transdisciplinarity

With respect to science–practice collaboration, *Erich Jantsch's* (Jantsch 1970) contribution at the 1970 OECD Conference on Interdisciplinarity is: Problems of Teaching and Research in Universities provided a visionary view of the transdisciplinary university: … *a transdisciplinary structure for the university* … [includes] *three types of organizational units – systems design laboratories, function-oriented departments, and discipline-oriented departments – which focus … the education/innovation system, i.e., on method and organization rather than on accumulated knowledge.* (Jantsch 1970, p. 403). Science–practice collaboration-based transdisciplinarity emerged from this idea of function-oriented departments.

At the same time, the US National Academy of Science and the Social Science Research Survey Committee addressed "social crises" and demanded that science contribute to an

> … increased depth of understanding human behavior and the institutions of society; and second, in better ways to use this understanding in devising social policy and the management of these affairs. (NAS 1969)

In the USA, Mahan Jr. (1970) also suggested the concept of transdisciplinarity. Yet, the notion of transdisciplinarity was, finally, restricted to an integrative, theoretically, and methodologically based (i.e., "true") interdisciplinarity that provided concepts for better understanding the foundations of authentic social behavior (e.g., for concepts such as "general behavioral principles"), for instance, when providing concepts such as "general behavioral principles" (Mahan Jr. 1970, p. 20). Collaboration with practice was neither discussed nor considered.

Around 1970, traditional criteria and rationales for disciplinary science came under pressure. *Interdisciplinary fields* and *applied research* acknowledged the complexity of societal structures and problems as well as the demand by practice to benefit from universities and public knowledge institutions (such as the Max Planck Institutes). Some scientists have argued that traditional forms of validation are no longer possible in complex systems, and singular casualties have become unimportant (see, e.g., post-normal science; Funtowicz and Ravetz 2003). The traditional science standards were further undermined by commercial interests in applied projects and fraudulent scientific papers driven by academic career pressures (e.g., "publish or perish"). Thus, it became increasingly difficult to define what *good science* is and what can be considered as a validated or even proven reference from the practitioner side, e.g., governments, courts, business and industry, and the public at large.

The increasing challenge of distinguishing between research conducted by science and that undertaken by practice can be illustrated by the *Triple Helix Model* of university–industry–government relations (Etzkowitz and Leydesdorff 1995) and the *Third Mission* (Asplund and Nordman 1999) approach. The term *Third Mission* has been utilized in many contexts and has mostly denoted the utilization of universities beyond scientific research and academic education. In 1994, Director of the Cornell Program on Dairy Markets and Policy Andrew M. Novakovic defined the goal of the Third Mission:

> *The third mission is to assist and advise members of industry and policy makers as they seek to understand or develop dairy policies or new marketing institutions, mechanisms, and practices.* (Novakovic 1994)

Overcoming the bottleneck of funding shortages with yields from the *marketification* and *commodification* of research and higher education (Laredo 2007; Zomer and Benneworth 2011) was the key driver for the formation of the Third Mission. The public expected the university to contribute revenue to their investment by providing contract-based services to industrial and governmental interests, and this demand has nourished the heterogeneity of universities and flattened the boundaries between the university and private consultancy companies that also apply scientific methods.

Etzkowitz and Leydesdorff (1995) extended the Third Mission concept to the Triple Helix concept, which is a slight revision of Clark's "triangle of coordination" (1983) between the "academic oligopoly" (i.e., the universities), the market (i.e., the economy, commercial users), and the state authority (i.e., politics and/or the state).

> *Boundaries between public and private, science and technology, university and industry are in flux. … Companies increasingly look to universities, …, as a potential source of useful knowledge and technology …, often encouraged by government – at both regional and national levels* …. (Etzkowitz and Leydesdorff 1998, pp. 203–204)

The concept of the Third Mission was further extended because of governments' needs to implement political programs. For instance, the social and planning sciences "were facing a shift of funding toward policy programs" (Zomer and Benneworth 2011). Urbanization and the development of sustainable cities have been key topics in this context, and societal needs and the demands for urgency, usefulness, and societal relevance have gained significance. As a consequence, new departments, curricula, institutions, and universities of applied sciences have been established to meet these needs.

Undoubtedly, business and industry interests have been the primary engines driving the Third Mission. A structural analysis has also been provided by the groundbreaking book *The New Production of Knowledge* and the concept of Mode 2 research, meaning "Mode 2 knowledge is carried out in the context of application" (Gibbons et al. 1994). The idea of contract-based research with *professors as* (low-cost) *knowledge workers* (Scott 2007) highlights this. The conception of the *entrepreneurial university* emphasizes the North and South American view (Thorn and Soo 2006) of the Third Mission. Much earlier, Clark (1983) had become aware of national (and cultural) differences. For instance, in Swedish universities, not only "economic life" but also the total "surrounding society" were seen as subjects of the Third Mission.

Another critical fact is that, for more than a century, a significant share of research has been conducted by large private companies in open or covert cooperation (Bernal 1954/1965; Scholz 2020). All these maintain high-profile research departments that promote marketable products as well as important scientific findings as a secondary product (which can also be published in high-ranking journals as long as a company's competitive advantage is not endangered).

What are the characteristics of knowledge produced by science and practice?

The conception of the considered type of transdisciplinarity relies on the complementarity of science and practice. This complementarity is often not shared or understood, primarily by scientists. To overcome this, we describe the drivers, rationales (epistemics), reward systems, and the societal role of science and practice. This allows to understand who, e.g., a senior biochemist who is doing research for a pharmaceutical company follows different goals from a colleague employed at a public university (and why their work falls under the purview of different ministries).

The science–practice complementarity was, first, inspired by the distinction between Mode 1 and Mode 2 science (Gibbons et al. 1994). Mode 1 deals with a "discipline-based" setting and by problem-solving of and for academic communities. Mode 2 science draws "on sources beyond any set of disciplines … because not all participants in knowledge production come from universities. Some might come from government laboratories, some from industry, and others from social action groups and concerned citizens perhaps with no particular scientific training at all. In Mode 2 everyone has something to contribute to the formation of a research agenda." (Gibbons 2013) Second, one may consider "science–practice" complementarity as a generalization of the discussions in psychology, nursing science, and related fields about this distinction (Hoshmand and Polkinghorne 1992; Sheppard 1995). Third, Scholz (2011) distinguished between the drivers and rationales of different human systems, e.g., between scientists (working at public or non-profit institutions to produce knowledge as a public good; being paid by the taxpayers) and practitioners. For instance, the driver of scientists who are operating in Mode 1 is to contribute to better understand reality (i.e., approaching truth), which is the search for fundamental knowledge, consistent reasoning, academic acknowledgement, etc. These goals have been described by Merton (1973) or Bunge (2012). Naturally, there are also Mode 2 scientists working on societally relevant problems who operate in a public good frame. On the other hand, practitioners' primary drivers are supposed to be successful when being capable of solving practical problems. The commercial driver of market success or the politicians' drivers to become elected may be taken as examples.

Given the complexity of coupled human–environment systems, knowledge from all domains of science, in principle, is relevant from a sustainable-transitioning perspective (Matson et al. 2016; Scholz 2011). In this context, we acknowledge that, from an epistemological perspective, practitioners' experiential knowledge is necessary for a holistic framing that allows for an adequate conceptual structuring of complexity and for a proper understanding of the role of contextualization in the practical significance/

relevance of ill-defined or wicked societal problems. The key role of science is to provide a consistent and theory-based description and model depicting as many of the properties, structures, causalities, and dynamics of a system as possible. Scientific statements are empirically validated as far as possible. This holds true not only for controlled laboratory settings, but also for settings coping with real-world problems (see Table 1).

Here, the first obstacle is to decide which scientific knowledge and theories are helpful to better represent a complex real-world problem. In this context, one specific challenge is to identify the state of the art in science, which consistently labors under the specter of unavoidable incompleteness; this is, nevertheless, an intrinsic element of the scientific process. Thus, scientific theories never completely and finally describe "reality." Given a specific problem, some theories are more adequate than others and some fail to meet the contemporary criteria for scientific quality. As characterized by Sarewitz (2000), "science is sufficiently rich, diverse, and Balkanized to provide comport and support for a range of subjective, political positions on complex issues." This asks for processes which avoid immature or biased scientific studies taken as truth.

An even greater challenge in science–practice collaboration for sustainable system transitioning is coping with *normative and cultural dimensions*. The normative dimension is intrinsic not only on the practice side: scientific theories depend on the worldview (i.e., cosmology) and the Zeitgeist. This is the case for the social sciences and the humanities, but we can also find extreme cases in the natural sciences. For instance, during World War II, the Nazi regime abandoned nuclear physics promoted by the German Nobel laureates in physics, Stark (1937) and Lenard (1936), in favor of developing Aryan physics (excluding probabilistic fuzziness). Within the social sciences, psychology might serve as a prominent example. Behavioral psychology may be taken as a contemporary example, as it almost exclusively traces the relation of behavioral responses to environmental stimuli. In contrast, humanistic psychology takes a much broader view, integrating "knowledge of the individual's mind, body, and behavior within an awareness of social and cultural forces." This means that scientific approaches themselves are value laden and include normative assumptions. We argue that science–practice dialogs have to communicate the normative assumption on both sides, science and practice; for example, approaches that lack rigor or are characterized by extreme normative assumptions should be excluded. The message is that normative values are included in science to some extent (Scholz 2017), but we should ensure that they remain subordinate and that scientists reveal the basic components of their worldview in an open manner.

Ensuring the utilization of scientific state-of-the-art knowledge based on consistent theories and—if the subject allows—sufficient empirical validation represents a more specific challenge. As matters addressed in science–practice collaborations are often complex, a specific challenge is relating the pivotal elements of a real-world system analysis to scientific insights and conclusions.

The basic properties and functions of science knowledge are described in Fig. 1.

In its ideal form, *scientific knowledge* is general and fundamental in the sense that it explains a large domain of reality. Natural science is universal, as all aspects of the universe are subject to the same natural laws. Scientific theories are consistent, and empirical validation takes place based on scientific methods. We distinguish between codified and written knowledge and the living aspects of knowledge that exist within scientists and their communities. According to Piaget's genetic epistemology (1968), an individual's higher-ordered (abstracted) knowledge cannot be acquired through everyday knowledge. Higher-ordered knowledge is based on the acquisition of key elements of knowing and methods practiced in higher-educational and research institutions that convey abstracted and scientific knowledge, which has developed over the course of human phylogenesis. The development of cognitive knowledge is moving along the path (stages) of phylogenetically acquired and codified levels (e.g., concrete operations on matters we may visually imagine/experience are preceding abstracted formal operations). This calls for competent educational institutions at all levels that maintain, condense, and develop (abstracted and) scientific knowledge and standards (see Fig. 1, upper part).

Practice knowledge serves to master life and to cope with complex real-world problems. It is seen as a foundation of skills and competences underlying behavior (Risopoulos-Pichler et al. 2020). Practical knowledge is based on (economic) heuristics and functional (simple) heuristics (Gigerenzer 2021), thus following the satisficing principle. Also practitioners' experiential knowledge includes abstraction and reflective observations on real-world settings (Kolb 1984). Practical knowledge is shaped by and embedded in attitudinal, motivational, emotional and personal, and contextual factors. Simplified, it serves to meet the needs and—sometimes—idiosyncratic objectives of individuals and other human systems.

Reflections on and motives for science–practice collaborations

When reflecting on the reasons practitioners choose to collaborate with scientists, based on the proposed complementarity of knowledge, we identify the following primary motivations. Science helps to structure (Mingers and Rosenhead 2004) complex problems in natural, social, and technological systems. It also describes major causal impacts and their interactions in a qualitative and

Table 1 Classification of types of science–practice collaboration along the process ownership scale (Fig. 2)

	Types of science–practice collaboration	Origin or prototypical example	Characteristic properties	References
1	Applied science (partially including practitioners)	Edison's inventions for light, electric power supply, etc.	Science addresses real-world problems Scientists do their research autonomously	Bunge (1966)
2	Ethnographic research/cultural anthropology	Street-corner society (Whyte 1943)	Subjective (personalist), participant observation Scientists work within the practitioners' world, but stay independent	Whyte (1943), Whitehead (2005) and Spradley (2016)
3	Participatory research	Planning cells; community development	Scientists involve practitioners in parts of their research to better understand the context and complexity	Dienel and Renn (1995), Cornwall and Jewkes (1995), Rahman (1991) and Christopher et al. (2008)
4	Science-shop-like knowledge transfer	Science shops	The provision of scientific research relevant to civil society The topics actually dealt with depend finally on the scientists	Leydesdorff (1980) and Fischer et al. (2004)
5	Team science/translational research	Hospital management and health science	Team science as a specific form of applied interdisciplinarity The scientists usually are on top of the hierarchy of the different actors involved	Stokols et al. (2008), Nowotny et al. (2001), Bennett and Gadlin (2012) and Drolet and Lorenzi (2011)
6	Citizen science	Biodiversity Citizen Challenge (California)	Citizens with sufficient knowledge about a subject of interest serve as "local researchers," e.g., community-based environmental monitoring Projects are initiated and led by scientists	Cohn (2008), Cooper et al. (2007) and Silvertown (2009)
7	Transition management	The Dutch energy system	Scientists relate different societal trajectories in the form of "partisan mutual adjustment" for societal change (Kemp et al. 2007, p. 79)	Rotmans et al. (2001), Kemp et al. (2007) and Rotmans and Loorbach (2008)
8	Action research	Kurt Lewin's focus on minorities (e.g., Jews, African Americans)	Attaining scientists' normative goals in practice Preparing and doing actions and problem-solving together with practitioners	Lewin (1946), Freire (1993), Whyte et al. (1991) and Kapoor and Jordan (2009)
9	Community-based participatory research (CBPR)	When patients are recognized as experts with experience and skills that complement those of researchers (clinical research)	Involves subjects or organizations that deliberately and consciously participate in a research project	Wallerstein and Duran (2017, 2010), Israel et al. (2017) and Wilson (2018)
10	Mode 2 Transdisciplinarity	According to Zurich 2000 as a normal science approach	Equal footing among science and practice For complex, societally relevant problems; linking interdisciplinary applied research and multistakeholder discourses for capacity building/socially robust orientations	Jantsch (1970), Häberli and Grossenbacher-Mansuy (1998), Scholz et al. (2000a, b, 2006), Lang et al. (2012) and Scholz and Steiner (2015a)
11	Triple Helix/Third Mission	Dutch "political power game," e.g., Dutch energy system	Utilization of universities beyond scientific research and academic education for attaining industrial or political goals	Leydesdorff and Etzkowitz (1996), Etzkowitz and Leydesdorff (1998) and Etzkowitz et al. (1998)

Table 1 (continued)

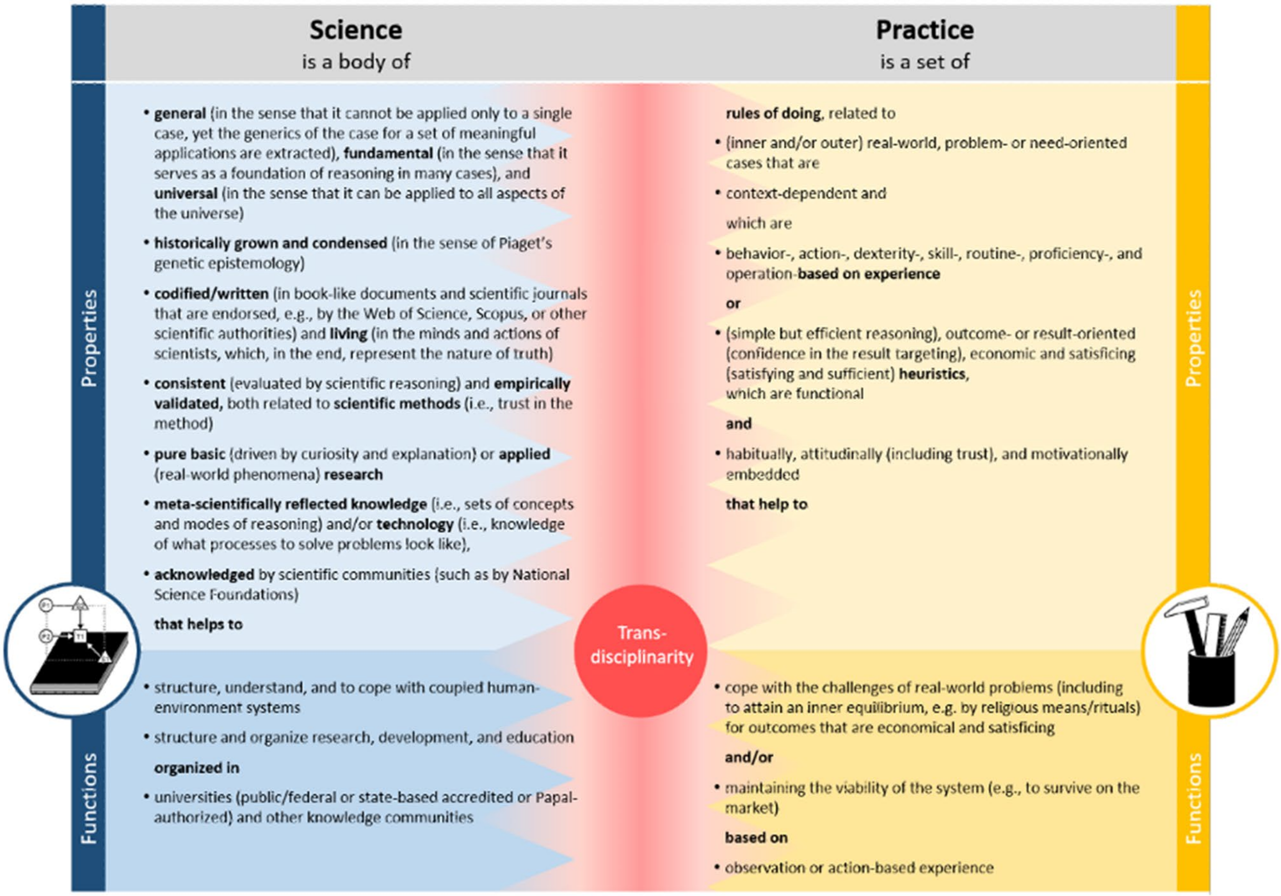
	Types of science–practice collaboration	Origin or prototypical example	Characteristic properties	References
12	Public participation	Citizens participate in urban planning processes	Research in a context where the public at large participates and influences the decisions made for specific societal challenges Actors of public institutions keep full control (formally)	Dienel (1970/1991), Newig and Fritsch (2009), Newig et al. (2005) and Devecchi (2012)
13	Open innovation	Industry includes consumers in product development	Opening up their organizational system to engage other external experts from science and practice Business and industrial actors keep full control	Chesbrough (2003), Gassmann et al. (2010), Du et al. (2014), Melese et al. (2009) and Mention (2011)
14	Contract-based research	Fraunhofer mission	Opening up the own organizational system to engage other external experts from science and practice The research to be done is fully described in the contract, and practice keeps control of the publications	Graydon (2012)
15	Consultancy	HKS's consultancy work on governments and public administration	Scientists/experts provide specific advice in policy/political or business fields (as a variant of consultancy)	Sturdy (1997), Hoppe (1999) and Pielke (2002)

quantitative data-based way. This may result in a principal risk assessment where different sources of knowledge are needed (Jasanoff 1993; Renn and Klinke 2004).

Given a complex problem, the challenge is to identify the key factors, subsystems, and entities and their (rules of) interaction for providing a robust representation of the system's basic dynamics. Scientific knowledge may be related and "drawn upon" the situated knowledge, both in a reflective manner and to provide a "conceptual language" to understand and reflect on "experienced complexities" (West et al. 2019, p. 534).

Actually, practice has a long list of demands to which science may contribute. These include solving complex real-world problems, improving human well-being, governmental counseling, consulting non-political clients, resolving conflicts and disputes, capacity building and empowerment, identifying options for changing the world to improve living situations, creating pathways to the future (e.g., understanding barriers to and mechanisms of societal change and digital transformation, developmental aid), managing resilience, and generally, explaining how the world and the universe function. Most of these examples call for problem-driven applied research.

Scientists' motives for collaborating with practice are equally wide ranging. The wish to escape the ivory tower can be motivated (a) by a desire to contribute to societal problem-solving (doing something good for society or earning money for the university or for oneself). Often, (b) collaboration with practice by means of participatory research is needed to gain access to certain data. Particularly in applied research, not only knowledge from different disciplines, but also (c) practitioners' concrete contextual and historical system expertise is needed for developing an appropriate system model. This was demonstrated by Wynne's (1996) case studies on the nuclear-waste assessment of sheep pastures. Scientists were unable to differentiate between historical nuclear fallouts (e.g., nuclear testing around 1950, the Windscale fire in Sellafield in 1957, and Chernobyl in 1986). It was farmers' practical knowledge about their sheep's grazing behaviors that made it possible for scientists to differentiate between the different sources of nuclear contamination. Thus, farmers were contextual experts for the concrete, real-world system. They represented and owned an intuitive, holistic, experience-based method of knowing or epistemics (Dreyfus and Dreyfus 2005), which will always be the case. In a more generalized sense, there are many questions for which science requires practical knowledge. Another example is the case of presumed mineral phosphorus (P) scarcity (essential for global food security). Here, geo-economical experts reject the environmental scientists' erroneous modeling of peak phosphorus in 25 years (Scholz and Wellmer 2021).



Science
is a body of

- **general** (in the sense that it cannot be applied only to a single case, yet the generics of the case for a set of meaningful applications are extracted), **fundamental** (in the sense that it serves as a foundation of reasoning in many cases), and **universal** (in the sense that it can be applied to all aspects of the universe)
- **historically grown and condensed** (in the sense of Piaget's genetic epistemology)
- **codified/written** (in book-like documents and scientific journals that are endorsed, e.g., by the Web of Science, Scopus, or other scientific authorities) and **living** (in the minds and actions of scientists, which, in the end, represent the nature of truth)
- **consistent** (evaluated by scientific reasoning) and **empirically validated,** both related to **scientific methods** (i.e., trust in the method)
- **pure basic** (driven by curiosity and explanation) or **applied** (real-world phenomena) **research**
- **meta-scientifically reflected knowledge** (i.e., sets of concepts and modes of reasoning) and/or **technology** (i.e., knowledge of what processes to solve problems look like),
- **acknowledged** by scientific communities (such as by National Science Foundations)

that helps to

- structure, understand, and to cope with coupled human-environment systems
- structure and organize research, development, and education

organized in

- universities (public/federal or state-based accredited or Papal-authorized) and other knowledge communities

Practice
is a set of

rules of doing, related to

- (inner and/or outer) real-world, problem- or need-oriented cases that are
- context-dependent and

which are

- behavior-, action-, dexterity-, skill-, routine-, proficiency-, and operation-**based on experience**

or

- (simple but efficient reasoning), outcome- or result-oriented (confidence in the result targeting), economic and satisficing (satisfying and sufficient) **heuristics**, which are functional

and

- habitually, attitudinally (including trust), and motivationally embedded

that help to

- cope with the challenges of real-world problems (including to attain an inner equilibrium, e.g. by religious means/rituals) for outcomes that are economical and satisficing

and/or

- maintaining the viability of the system (e.g., to survive on the market)

based on

- observation or action-based experience

Fig. 1 A property- and function-based definition of science and practice

Box 1: Methodology of the construction of the process ownership scale

What are the main differences between the various approaches of science–practice collaboration? Answering this question was a four-step process that spanned several years. Step 1 consisted of identifying 15 different approaches based on the authors' theoretical and practical experience (Scholz and Steiner 2015c, 2016) and responses from their network, conferences, workshops, etc.

Step 2 was a multi-dimensional scaling of these approaches. This was done by identifying the unique selling points (USPs) and by constructing a Likert-scale agreement statement for each USP. This reads, e.g., as follows "Consulting: Client specific problem-solving: The only purpose is to (help to) solve specific problems which are formulated (and thus in the interest) of a certain practitioner." Both, a principal component analysis (PCA) and a cluster analysis (CLA) provided compatible groupings of the approaches/UPS. The PCA provided the factor "F1: joint leadership and mutual learning" as a kind of general factor (extracting 28% of variance). It was followed by "F2: Third Mission for the public" (which was obviously limited to the public change side). The factor F3 is "Consulting for reflection of clients" (13% extraction of variance).

Step 3 includes an integration of the results of Step 1 and 3. The list of approaches got refined (e.g., by considering six subvariants of transdisciplinary). The two main clusters were labeled "Interactive methods of science–practice collaboration" (such as translational research which exists since 1915) and "Conventional science for practice" approaches where science takes the lead. When comprising "co-leadership" and "mutual learning" to equal governance (and benefits) and acknowledging that both major clusters also differ with respect to who takes the lead, the "process ownership scale" emerged. A second dimension, capacity building vs. solutionism, is not dealt with in depth in this paper. The three steps led to the process ownership scale.

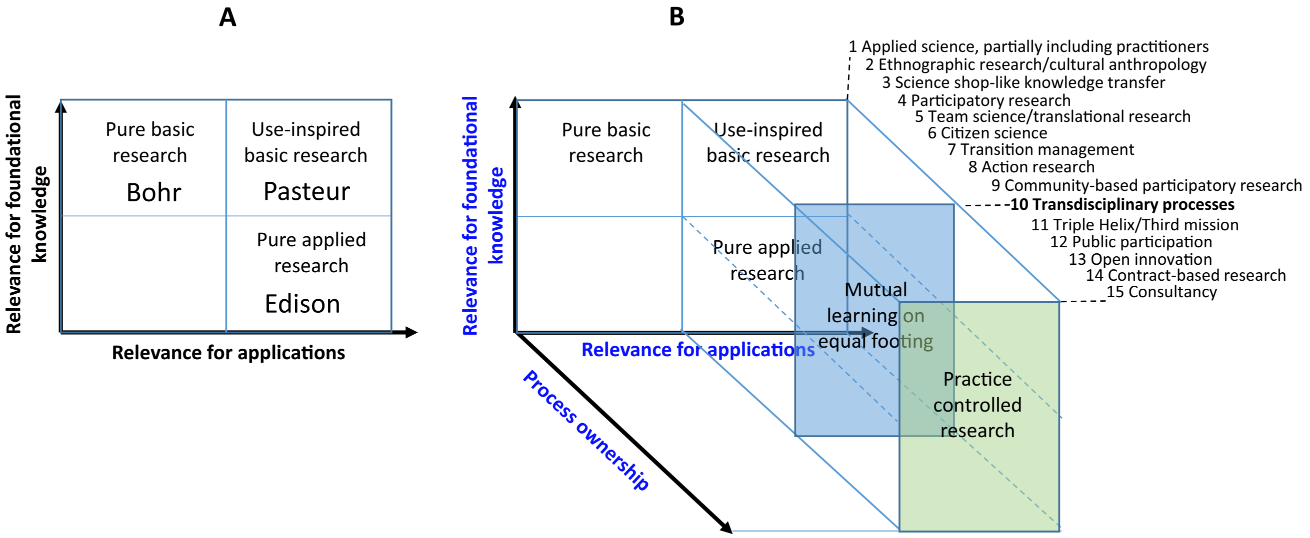


Fig. 2 Extending Pasteur's Quadrant (**A**) by the process ownership scale for 15 types of science–practice collaboration (**B**); the axes are of ordinal scale (for definition and literature see Appendix)

Step 4 consisted of updating the former list of approaches (see Appendix) and of a (double) rank ordering of the approaches with a stronger/weaker process ownership by practitioners and resulting in the scale as shown in Fig. 2B. Attention was paid with respect to complementarity and to differences in process ownership. Thus, Living Labs (German Reallabore) were judged in between action research and community-based action research and not included as its own category. The suggested rank ordering was done by the authors and thus subjectively biased. How the science community or main representatives of an approach locate the approaches on the scale may become subject of empirical research

Process ownership in science–practice collaborations

The selection, definition, and differentiation among the different approaches took a multi-year process. The process for developing the process ownership scale is described in Box 1. Simplified, the process of generating the ownership scale is divided into the sub-concepts, co-leadership and mutual learning. It is a kind of G-factor in the multivariate analysis of the unique selling points of the 15 approaches. Process ownership meets a critical concern of science–practice collaboration, i.e., the question of who takes control of the collaboration process. This includes, particularly, who is the principal in defining the research question, who takes data ownership, and who decides in what way(s) the results are used and published. Scholz (2020) distinguished between *independent applied research* and *contract-based research.*

Forms of science–practice collaboration differ widely depending on who takes *process ownership*. We argue that *process ownership* became an important characteristic of conducting applied and use-inspired basic research in the frame of Pasteur's quadrant, which was introduced by Stokes (1997). Stokes distinguished between *relevance for applications* and *relevance for fundamental knowledge* (the *x*-axis and *y*-axis of Fig. 2A). Classical pure basic research was represented by Niels Bohr (and his research on the foundations of nuclear physics). Stokes's message was that we may distinguish two types of applied research. One, often associated with Thomas Edison's work, is oriented toward problem-solving and is close to what practical engineers are doing. The other has been called *use-inspired basic research.* Here, Louis Pasteur's biochemical approach to vaccination serves as the model. Overall, since the development of Mode 2 science (Gibbons et al. 1994), the interaction and collaboration of science and practice have shaped many domains of science (and not only technical universities).

The poles of the process ownership scale

There are two poles on the process ownership scale. Seen as one extreme is the classical university-hosted *applied science*, which only partially includes practitioners *[1].* All numbers in italicized square brackets represent ranks of process ownership presented in Fig. 2B along the *z*-axis (CSS 2022). The highest degree of independence in applied research (practiced in democratic countries) is provided by university or science-foundation funding (public or private) that is not related to specific thematic research programs and seeks only high-level (peer-reviewed) research. Specifically, we may say that this kind of scientific research is typically conducted in a university's highly protected (though competitive) comfort zone. At the opposite end of the pole is *contract-based research [17]*, where a principal takes control of the research process. Here, we may think about pharmaceutical-approval studies or political research on opinion formation regarding political programs. The research question formulated and the design selected, whether a study is published, and other important constraints are, ultimately, controlled by the principal. This type of research can be conducted by both public and private laboratories and institutes.

Variants of transdisciplinarity

Transdisciplinary processes in which active collaboration between science and practitioners takes place (Renn 2021; Scholz and Steiner 2015a) represent the midpoint of the process ownership scale, i.e., a kind of inflection point *[10]* between science and practice leadership dominance. In an ideal transdisciplinary process, scientists and practitioners meet on an equal footing to better understand, conceptualize, and describe a complex real-world problem aimed at both improving practitioners' decisions and actions and providing scientists with a better understanding and structuring of a problem that is scientifically challenging and not yet sufficiently understood. Scientists and practitioners take joint responsibility for the process and its results, based on an authentic process of mutual learning. This can best be achieved by taking co-leadership when accepting the otherness of the other's roles and interests (Polk 2014; Scholz and Steiner 2015a); thus, practice leaders must know that scientists develop theories by writing papers. To do so, scientists need certain data that are not of immediate interest for solving practical problems. For their part, scientists must delve into real-world problems and *empower practitioners* to share their experience for finding solutions that secure the viability and resilience of relevant practical subsystems and processes (of their interest). This requires an equitable appraisal of high-quality knowledge from practice and from science. Although, ultimately, the practitioner takes responsibility for the practical decisions and the scientist for the theories and publications, there is some joint accountability and responsibility for the process and for socially robust orientations, for instance to system transitions, seen as the major outcome of a transdisciplinary process. The socially robust orientations emerging from transdisciplinary science–practice collaboration may serve as orientations, signposts, and guardrails for sustainable development.

From an operational perspective, co-leadership means that both sides, science and practice, actively participate with equal rights and terms in all essential issues of (1) the preparation phase (including the negotiation of the goals and the guiding question), (2) the process planning (which includes stakeholder analysis and selection of those who participate and the process/schedule and structure/organizational chart of a project) including the joint problem representation, (3) the core phase (including products which are produced, reviewed, and evaluated), and (4) the post-processing phase in which the results are used. Please note that co-leadership should be formally or informally ratified and communicated internally and externally. In transdisciplinary processes, co-leadership and balanced participation should take place at all levels (e.g., subprojects). All critical issues (e.g., what results are communicated how) ask for an explicit joint agreement. This may ask for ratified codes of conduct.

Naturally, the operational lead in certain activities may be allocated to science (e.g., in scientific modeling) or to practice (e.g., in practice networking) (Krütli et al. 2010; Stauffacher et al. 2008). Yet, both sides may ask for full transparency and negotiate whether and how outcomes are used. It is important to reflect on the implicit power relations which may cause asymmetries, e.g., if science frames the process by certain methods. Rosendahl et al. (2015) refer to feminist standpoint theory and stress that transdisciplinary processes require "the explicit and transparent positioning of oneself: this also holds true for scientists." (Rosendahl et al. 2015, p. 26).

Transdisciplinarity often serves as a method for *strategic sustainability planning and management* (Matson et al. 2016). This means, for example, that participatory formative scenario construction and evaluation are conceived as a joint venture of practitioners and scientists. For certain stages, e.g., goal and system definition, both contribute equally, while—depending on the problem to be solved—the guiding hand may be on the science or practice side (the phases of different leadership are illustrated by Krütli et al. 2010). Thus, for consistency and resilience assessment in scenario construction, scientists may take the lead, and for other subprocesses, e.g., scenario interpretation and the development of implementation strategies, practitioners lead.

Of note, similar definitions of transdisciplinarity exist that do not stress co-leadership (Lang et al. 2012), but instead target participatory research when including practitioners. The version we presented emerges from a realist, normal science conception, while some transdisciplinary researchers refer to a post-normal conception as proposed by Funtowicz and Ravetz (2003). A key claim of this view is that classical scientific theories lose their value in complex, contextualized settings (Klein 2004). Yet, the post-normal approach to transdisciplinarity often remains in the frame of theoretical reflection when it is considered without processes of co-leadership and authentic collaboration with practitioners.

Transdisciplinarity also plays an important role in overcoming the widespread hostility toward the traditional prospects of research on indigenous peoples, which were also labeled the Europeanization or colonization of research

(Smith 2013). An early contribution to transdisciplinarity is Article 10 of the "Manifesto de transdisciplinaridade" which declares "No single culture is privileged over any other" (Morin et al. 1994). In other words, indigenous knowledge, as a form of situated knowledge, is different, but of equal value to abstracted Western science knowledge. The latter is included in the "accepting the otherness of the other" principle of transdisciplinarity presented above, which may be seen as a prerequisite of equal process ownership in intercultural studies.

Other forms of science–practice collaboration

Several types of science–practice collaboration show some similarity to transdisciplinary processes. We consider variants of community-based participatory (action) research (Israel et al. 2017; Wallerstein and Duran 2017) to be very close to transdisciplinary processes and slightly in the direction of dominant science process ownership *[9]*. There are three main differences from the by us proposed conception of transdisciplinary processes. The first is full co-leadership (thus, related to the potential threat of losing control of the process). The second is the aspiration of transdisciplinarity that transdisciplinary processes may result in certain types of directed, use-inspired research and, thereby, affect, enrich, and transform scientific disciplines (i.e., the impact of transdisciplinarity on science). Third, transdisciplinarity, as we conceive it, considers practice knowledge and science knowledge as essentially different (see Fig. 2), but equally important. Precedence in the course of a transdisciplinary process depends primarily on the type of problem under consideration. There are numerous projects in community health and community design which follow the conception of community-based participatory (action) research in the United States not using the term transdisciplinarity (Kessel et al. 2003).

There are other forms of action research *[8]*. In this type of science–society collaboration, scientists' societal concerns and interests become important. Lewin's (1946) seminal experiential action research was motivated by his interest in how minorities (Jews and Black Americans) fail to adapt. Lewin utilized analysis of variance (ANOVA) to measure the variation among and between groups regarding the effects of contextual factors and interventions. Today, we find a wide range of variants of action research, one of which, for example, is "shallow" activistic action research. Here, attaining scientists' normative goals in practice is the major aim and key validation criterion. Please note that the ANOVA models have also been used in transdisciplinary processes for tangible matters such as smallholder farmers' maize yields, where it helps to measure the effect of farmers' participation in a transdisciplinary mutual learning process (Njoroge et al. 2015) or to analyze different stakeholder groups judgments on future scenarios (Scholz and Stauffacher 2007).

In action research, scientists often become science activists or normative advocates who take broad control over goals, processes, and outcomes. About 27% of sustainability science researchers running processes including stakeholders judged that the scientist is "a stakeholder himself, bargaining for his interest" (Mielke et al. 2017, p. 10651). In the well-elaborated Dutch approach for transition management (*[7]*; see e.g., Loorbach 2014) a co-evolution of science and practice toward sustainability is targeted, in particular when ignoring mainstream incrementalism, and aspiring a pluralism in "partisan mutual adjustment" (Lindblom 1979, p. 522). Scientists may even function as niche partisans (e.g., when collaborating with grassroot movements; see e.g., Loorbach et al. 2020). In fact, this might become necessary, given certain autocratic structures, for example, if other types of research are not allowed or not funded.

Initially, citizen science *[6]* emerged from environmental sciences. In ecology, citizen scientists serve as "sensors" (Goodchild 2007, p. 211) to increase "the scale of ecological field studies with continent-wide, centralized monitoring efforts and, more rarely, tapping of volunteers to conduct large, coordinated, field experiments" (Dickinson et al. 2010, p. 149). Thus, citizens frequently serve as unpaid, part-time research assistants. Yet, most "citizen science projects also strive to help participants learn about the organisms they are observing" (Bonney et al. 2009, p. 977) and thus contribute to developing bioliteracy (Hooykaas et al. 2019). Current citizen science develops strategies for stakeholder selection and collaboration. From a societal perspective, the involvement of volunteers in research has increased the scale of ecological field studies with continent-wide, centralized monitoring efforts and, more rarely, the use of volunteers to conduct large, coordinated, field experiments (Dickinson et al. 2012). Yet, the validity and reliability of data collected by citizen scientists require critical reflection and evaluation (Clare et al. 2019).

As expressed by the phrase "bench to bedside," part of the foundation of the Journal of Translational Research in 1915, translational research *[5]* built the bridge between (biological) laboratory, medical technology developments and patients' needs. Although, in principle, this includes a number of commercial and clinically driven interests, many approaches, such as Stokols's team science (Stokols et al. 2008), are typically dominated by interdisciplinary science teams. Two features of this type of research are related to our conception of transdisciplinarity. First, team science utilizes targeted (use-inspired), interdisciplinary research for tangible (not only medical) real-world problems. Second, the teams usually include scientists and practitioners applying their complementary knowledge.

Often, the term participatory research *[4]* is mixed with transdisciplinarity. We consider *participatory research* a form of applied science, which (discontinuously) includes practitioners to better understand context and complexity or for an integrated assessment, for example, of climate impacts in a certain region (Salter et al. 2010). Sometimes in participatory research (such as in team science), who is participating in whose venture is unclear. In general, scientists maintain control regarding the form and intensity of science–practice collaboration. Mobjork (2010) differentiated "participatory transdisciplinarity" as presented above from "consulting transdisciplinarity" in which actors have the role of responding and reacting to the research conducted and researchers bear their thoughts and perspectives in mind during the research; the societal actors are not actively incorporated into the knowledge production process. Actually, this is what we defined as action research. In social studies, participatory research may include processes of "sequential reflection and action, carried out with and by local people rather than on them" (Cornwall and Jewkes 1995, p. 1667). Studies of organizational management may benefit by including CEOs' ideas, principles, and visions for identifying novel patterns of organizational processes. We should mention that any transdisciplinary process includes participatory research as a basic pillar. According to a survey by Mielke et al. (2017), sustainability scientists include mostly politicians and members of civil society via workshops and interviews. From the practitioners' perspective, transdisciplinary processes contribute to the formation of a reflective practitioner (Schön 2017) who is able reflect in and on actions, e.g., by utilizing his/her experiences made in science discourses.

The science-dominated side of this process ownership scale continues with *[3]* a science-shop-like knowledge transfer (Leydesdorff and Van Den Besselaar 1987). Here, scientists usually decide whose questions are answered and whose are not. Finally, ethnographic research *[2]* (as used in geography, anthropology, and human ecology; Whyte 1943) includes strong, intimate mutual learning leading to interaction with, for example, indigenous people, yet it may be conceived as a valuable method for disciplinary applied science *[1]*.

The Triple Helix approach *[11]*, which may be considered a kind of elitist triad between industry, politics, and science (Scholz 2020), has been discussed extensively above. The term Third Mission is frequently used synonymously. We distinguish two lines of Third Mission-oriented science activities. One is the (typically industry-interest-driven) commercialization of science, which was highlighted by Etzkowitz:

> *The 'capitalization of knowledge' is at the heart of the entrepreneurial academic mission, linking universities to users of knowledge more tightly and establishing the university as an economic actor in its own right.* (Etzkowitz 2017, p. 128)

Etzkowitz's definition includes the peril that only research with market value will be funded. In the second line, research on and implementation of (governmental) policy programs is conducted under the Third Mission label. Usually, *contract-based research* is the form practiced in Third Mission. In fact, there is a broad range of contract-based research extending from framing the research topic to a meticulous and detailed description of outcomes and results *[16]* according to the sociopolitical interests of, for example, governmental funders. In both lines, we can identify the perils related to contract-based research that conflict with the principle of freedom of science.

Public participation [12] can be viewed as a governmental inclusion of stakeholder groups and scientists. It has been applied often in urban and regional development and for the identification of risk-management strategies for hazardous technologies (e.g., nuclear power plants). In general, setting agendas and deciding to end public participation are under the government's control. Several similarities exist between public participation and open innovation *[13]*; *open innovation* can be considered the business world's variant of participation. On the one hand, open innovation includes stakeholders and science knowledge at different levels of development; on the other, it aims at new forms of added commercial value. There are also solution-oriented institutes partially funded by the public. Such *contract-based research [14]* relies on delivery-note-like work packages. In general, industry and government *consultancies [15]* follow similar business principles, but often do not allow for independent research.

We argue that none of the presented methods is better than the others; all are means of science–practice collaboration. They differ with respect to process ownership, the key concept of structuring them in Fig. 2.

In the age of Anthropocene, human behavior has become a geological factor. Thus, natural scientists have become aware of the ozone hole, climate change, loss of biodiversity, and air and water pollution and eutrophication and have identified critical over-pumping of groundwater and overfishing on a large scale (see Cash et al. 2003). These previously unknown phenomena may affect the Earth's systems in ways that critically endanger the resilience of human life. Science should serve the public good, and scientists have the major dual responsibility to inform society about these challenges to empower governmental actors to reach effective and meaningful coping strategies (Jensen-Ryan and German 2019; Suni et al. 2016).

Discussion

Strengths and boundaries of transdisciplinary processes for socially robust orientations

The Zurich 2000 conference (Klein et al. 2001; Scholz et al. 2000a, b) can be seen as the start of the formation of transdisciplinary practice as a third mode of doing and utilizing science by doing science with society that complements disciplinarity and interdisciplinarity. Two issues were seen as key principles: first, *mutuality, in particular mutual learning* between science focus knowledge integration (Scholz 2000); second, there was the idea of authentic co-responsibility *and co-leadership* to allow for balance and efficiency when coping with wicked (or ill-defined), complex, value-laden, societally relevant problems that cannot be adequately managed using other approaches. Transdisciplinarity may be viewed as a means of strategic sustainable management. This paper elaborates that equal process ownership of science and practice (see Fig. 2) is a unique feature of transdisciplinary processes and may well serve as an umbrella concept. We used process ownership as a feature or dimension to differentiate different forms of science collaboration.

Equal process ownership also promotes the generation of *socially robust orientations* (Scholz 2011). These emerge from (1) integrating epistemics from science and practice to overcome the fragmentation of knowledge, (2) tapping into scientific state-of-the-art knowledge when (3) producing knowledge that can be understood principally by all representatives of stakeholder groups (and thus includes the potential for consensus formation, at least when defining a problem) and (4) which acknowledges not only uncertainties, but also the incompleteness of knowledge included (i.e., ignorance involved in any human knowledge) and (5) communicates the specific constraints (e.g., time, amount, source of funding, etc.) of knowledge production. Thus, transdisciplinarity is in contrast to many anti-differentiationists' view which "… deny the division between nature and culture, science and society, science and technology, and between research and enterprise" (Shinn 2005, p. 744).

Transdisciplinary processes of the presented type may even become a kind of tool for democracy if the stakeholders involved provide a balanced view of the interests of a spectrum of society. This is only possible if scientists and practitioners follow the basic rules of conduct of transdisciplinary processes, including accepting the otherness of the other and strictly confining to pre-competitive issues and excluding day-to-day politics. Thus, usually politicians are excluded (as they usually follow a shortsighted agenda) if they do not represent a public position. Usually, representatives of public agencies or positions take a balanced commons perspective.

The participation of representatives of key stakeholder groups and scientists (and the subsequent discussion) with equal process ownership serves to build capacity for sustainable decisions. Concrete action in business, day-to-day policy, applied research, etc., follows later. It is important to note that equal process ownership best, if not only, functions with real-world cases (settings; Vilsmaier et al. 2015). In all rules, the discussions on topics and themes are dominated by scientific disciplinary jargon and neither allows for a shared understanding of a problem nor the partnership with stakeholders. Case-based mutual learning guarantees a joint reference, which can be taken as a starting point and as a means for developing a shared problem understanding and problem representation when using and relating verbal, pictorial, numerical or formal mathematical representations (Jahn et al. 2012 talk about the formation of a common reserach object). Typically, mobility or energy transitions are studies in certain cities or areas, on plastic or phosphorus pollution in certain lakes or seas; insight into questions related to indigenous people are also studied on a case-based level. The description of reality of a real world provides an unambiguous reference which allows the identification of differences in risk perception, perspectives and values among the participants. Based on this, social solutions may be discussed and constructed.

Knowledge systems for actions of science–practice collaboration approaches

The presented, widely applied version (Scholz and Steiner 2015c) of transdisciplinary processes *[10]* is a *capacity for sustainable decisions* oriented one. But you may also find (direct solutionist, or) action-oriented *[8]* approaches of transdisciplinarity stating: "transdisciplinary research delivers high-quality solutions for practice actors facing societal problems" (Bergmann et al. 2012), which expresses a mission of action research. We think that this is rather a matter of consultancy *[15]*.

Sometimes, the knowledge-based differentiationist's complementarity of science and practice view (see Fig. 1; Shinn 2005) is given up (such as in "shallow action research" *[8]* or "transition management" *[7]*). Scientists themselves seem to become decision makers and actors. This poses new and challenging questions from a process ownership perspective.

- What is the moral and/or democratic legitimacy when scientists take process ownership [e.g., via the epistemic authority of the IPCC (Gustafsson and Lidskog 2018) or the IPBES (Shinn 2005)]?
    - Science must inform, but is political action part of science?

- When does advocacy science, as a driver of science process ownership, endanger the integrity of science?
  - How does worldview or political opinion affect the scientific knowledge produced? Can the mission of an honest knowledge broker (Pielke Jr. 2002) be fulfilled when taking an advocacy perspective?
- Is it necessary, under certain constraints, for scientists to take a solutionist, action-oriented approach *[8]* instead of a capacity-oriented one?
  - When must the knowledge- and epistemics-centered approach be overcome and action-orientation-based work come to the foreground?
  - Under what constraints is science process ownership necessary from a sustainable development perspective?
- What is the relationship of legitimized decision makers (e.g., working as coleaders) to elected policymakers or property owners (of land, resources, etc.)?
  - Must the role of process ownership be assessed differently in the democratically developed Western world, the developing world, and various autocratic countries such as China?
  - In what contexts do we face limited social degrees of freedom where scientists' processing of leadership may play an important role in breaking societal lock-in positions? What other methods (e.g., policy consultancy *[15]*) may be chosen, e.g., as an intermediate project to prepare the case for a transdisciplinary venture?
- How can we promote the dynamic change of science and practice headship which dynamically changes (depending on the task and topic; Stauffacher et al. 2008) to attain an overall balanced leadership?
  - Is it possible to measure the degree of involvement of scientists and practitioners? What aspects (e.g., controlling methods, fundings) endanger equal process ownership?

Conclusions and outlook

First, which form of science–practice collaboration is adequate depends on (i) the nature of the problem being addressed (e.g., what scientific or practical issue is the focus) and (ii) which actors are involved in what roles and with what powers, i.e., who takes process ownership. The latter includes which actors have control over the outcomes generated and who may utilize—and who may benefit from—data and other products of the process. This is also linked to (iii) the purpose of the collaboration. These three aspects allow us to better distinguish between participatory research (or citizen science) and transdisciplinary processes.

Second, equal process ownership of science and practice make transdisciplinary processes different from other forms of science–practice collaboration. Ideally, this results in authentic co-leadership allowing for collaboration and, thereby, co-creation, co-definition, co-design, co-representation, and co-responsibility. The product is socially robust orientations on sustainable transformation based on mutual learning between and within groups of scientists and representatives of key stakeholder groups. Such orientations produce more effective coping strategies for challenging wicked, complex, societally relevant problems. For these types of problems, each party (science and practice) is, on its own, overburdened for a variety of reasons related to the complexity and diversity of phenomena and impacts on different sociotechnological contexts, cultures, or scales. Practice and, in particular, key stakeholder groups that demonstrate a commitment to sustainability may learn which kinds of actions should be promoted and which should not. Moreover, science may become aware of the limits of disciplinary knowledge and what institutions are already available and capable of successfully providing targeted interdisciplinary processes as part of transdisciplinary processes for sustainable transitions.

Appendix

A description of the 15 approaches is provided in the text. Table 1 sets the approaches of Fig. 2B into context. This is done by illustrating the background of their development (column 2), by listing the key characteristics (column 3) and key references (column 4), which would help the reader to develop a deeper understanding of the approaches.

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