



Teaching scientific creativity through philosophy of science

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Abstract

There is a demand to nurture scientific creativity in science education. This paper proposes that the relevant conceptual infrastructure with which to teach scientific creativity is often already included in philosophy of science courses, even those that do not cover scientific creativity explicitly. More precisely, it is shown how paradigm theory can serve as a framework with which to introduce the differences between combinational, exploratory, and transformational creativity in science. Moreover, the types of components given in Kuhn's disciplinary matrix are argued to indicate a further subdivision within transformational creativity that makes explicit that this most radical type of creativity that aims to go beyond and thus to transform the current paradigm can take many different directions. More generally, it is argued that there are several synergies between the topic of scientific creativity and paradigm theory that can be utilized in most philosophy of science courses at relative ease. Doing so should promote the understanding of scientific creativity among students, provide another way to signify the relevance of paradigm theory, and more strategically be a way of reinforcing the place of philosophy of science in science education.

Keywords Creativity · Paradigm theory · Philosophy of science · Transformational creativity · Context of discovery · Thomas Kuhn

1 Introduction

There is a demand to nurture innovation and creativity in higher education. The European Union, for instance, lists among its four priorities for action in higher education the aim of “[e]nsuring [that] higher education institutions contribute to

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innovation” (European Commission 2017, COM/2017/0247 final:4). This, they qualify, entails that “[a]ll forms of higher learning should aim to equip students with the ability to understand new concepts, think critically and creatively and act entrepreneurially to develop and apply new ideas” (European Commission 2017, COM/2017/0247 final:8).¹ While this is high-level policy, Sybille Reichert (2019, 24) found in a survey among nine universities across Europe that concrete initiatives were taken at all institution to promote innovation as part of their degree programs. Thus, at least in the European Union, the expectation to cover innovation shapes individual courses and this expectation will likely find its way to philosophy of science courses as well; perhaps especially if the courses are integrated within science programs.² The present paper, however, proposes that philosophy of science should welcome this challenge to cover topics such as creative thinking and the development of new ideas among the elements of innovation emphasized by the European Commission.³ Scientific discovery and creativity are after all central themes to philosophy of science already (see Schickore (2018) for a survey). But philosophy of science courses are also *especially* well equipped to relate what creative thinking is because most philosophy of science courses already include an infrastructure with which to do so, as this paper argues. Furthermore, it is found that there are several synergies between the topic of scientific creativity and the traditional elements of a philosophy of science curriculum, paradigm theory in particular. Finally, by their relation to innovation, covering these themes may be a way to reinforce the relevance and place of philosophy of science within science education.

The argument, in brief, is this: When Margaret Boden (1991) – and with her many other researchers on creativity (e.g. Sternberg 2003; Schunn and Klahr 1995) – defines creativity as the generation of new ideas, the typology of novelties is explicated relative to a background framework of assumptions and practices. In science, one way of capturing such background frameworks is through scientific paradigms which are already introduced with some care in most philosophy of science courses, either through their original exposition by Thomas Kuhn (1970) or through later iterations such as those due to Howard Margolis (1993) and Paul Thagard (1992). The claim to be defended here is then that in philosophy of science courses the conceptual framework of paradigm theory broadly construed can double as an infrastructure with which to elucidate – and compared to Boden’s exposition, elaborate upon – what scientific creativity involves including the insight that not all creativity is the same. Furthermore, the Kuhnian disciplinary matrix can serve to signify that

¹ In identifying these components as part of innovation, the European Commission seems to follow the typical explication of innovation as a success term for when a creative idea is brought to fruition through the implementation in a relevant context (Shalley, Hitt, and Zhou 2015).

² Indeed, at the University of Copenhagen the compulsory philosophy of science courses integrated in the physics, chemistry, mathematics, informatics, biology, sport science, and computer science programs already require an explicit innovation component.

³ While the value of creativity is disputed in some quarters (see, e.g., Grant 2012; Hills and Bird 2019), this essay will assume that teaching scientific creativity is valuable. There is also a longer history to the contemporary promotion for creativity and innovation in higher education and elsewhere (see, e.g., Godin 2015; Mason 2017).

there are different dimensions along which scientific creativity can play out. The benefit, however, is mutual. Boden's insistence that ideas that preserve the background framework can nevertheless be creative serve to reinforce the point that also non-revolutionary science can qualify as creative. Likewise, Boden's category of combinational creativity that combines multiple frameworks suggests a type of scientific creativity that is next to incomprehensible at least on Kuhn's version of paradigm theory. As such, the present paper can be read as exploring some advantages in bringing together typologies of creativity and paradigm theory.

It is, however, relevant at this point to emphasize that only a limited perspective on creativity is covered when the focus is on typologies of creativity and how they can be explicated through paradigm theory. The literature on scientific discovery and creativity within the philosophy of science is rich and importantly has much more to say about *how* creativity is achieved and not just what it is. The limitations of the present approach to creativity will be discussed further in section 4 which also provides a concrete proposal for how to integrate the teaching of paradigm theory and scientific creativity. Before that, section 2 introduces paradigm theory, Boden's three types of creativity, and discusses their potential synergies. Section 3 focuses on transformational creativity and employs Kuhn's disciplinary matrix to introduce a subdivision within this type of creativity that is not identified by Boden.

2 Paradigm theories and types of creativity

Several authors have noted that Kuhn's construal of scientific research as relative to a paradigm already implies a proto-typology of scientific creativity (e.g. Sternberg 2003; Simonton 2004; Pope 2005; Andersen 2013). Thomas Nickles (2011) develops this Kuhnian account in more detail. According to Nickles, Kuhn's central insight about creativity consists in the rejection of the view that creativity requires divergent thinking, i.e. that creativity is an "unconventional, imaginative activity that disregards established rules to strike out in new directions" (Nickles 2011, 209). In Kuhn's paradigm theory, most research does not involve divergent thinking but takes the form of "normal science" that solves puzzles whose character and admissible solutions are set by the paradigm, though often without the paradigm giving the puzzles or their admissible solutions explicitly. Kuhn (e.g. 1970, 38) therefore insists that puzzle-solving is far from a trivial activity. This leads Nickles to the proposal that normal science, on Kuhn's view, should be considered creative despite its largely convergent character. Normal science with its focus on (esoteric) details is after all what produces the anomalies that, according to Kuhn, eventually bring about the major changes of a scientific revolution. Kuhn, in other words, implicitly distinguishes between two types of creativity: "The more modest sort of creativity involves working within a guiding framework that defines the research enterprise in that particular specialty area and thereby makes esoteric research intelligible. The divergent sort generates a new defining framework that sends the field in a different direction" (Nickles 2011, 211).

Boden's distinction between exploratory, transformational, and combinational creativity is one influential typology of creativity – or typology of ways creative ideas can be “surprising” (Boden 2018, 181) – in the literature (see Gaut and Kieran 2018a for some recent discussions).⁴ Boden develops this distinction on the general background of what she calls a “conceptual space” which is explicated as a “disciplined way of thinking that is familiar to (and valued by) a certain social group” (Boden 1991, 4).⁵ Examples include the styles and genres observed in esthetic undertakings and the theoretical background of scientific work. Boden then introduces exploratory creativity in the following way: “Whatever the size of the space, someone who comes up with a new idea within that thinking style is being creative in the [...] exploratory sense” (Boden 1991, 4). The conceptual space does not come equipped with a specification of what it includes and its content therefore remains to be explored. As Boden argues, such exploration “is creative, for in exploring its home-territory it discovers many formerly unexpected locations and it also changes the maps it inherits” (Boden 1991, 75). Changing the maps does not, however, involve a change to the conceptual space itself (this comes about through transformational creativity as introduced below). Rather, it is a change to our expectation of what the conceptual space contains.

Making a direct reference to Kuhnian puzzle-solving, Boden qualifies that “[e]xploration is involved even in non-revolutionary scientific research” (Boden 1991, 75). Indeed, the connection between Kuhnian puzzle-solving and exploratory creativity is rather straightforward: Both activities are restricted by an existing framework, and thus instances of largely convergent thinking, but they are still argued to be creative since the framework rarely gives specific instructions for process or outcome. Just like a conceptual space dictates the established “style” in a general context, so, too, does the paradigm within a scientific discipline. As Boden also indicates, exploratory creativity in science can thereby be introduced as those instances of normal science that find “unexpected locations” in the conceptual space that a paradigm provides for.⁶ Sintonen (2009) makes the related suggestion that Boden's conceptual spaces can be modelled by Thagard's (1992) conceptual systems account of paradigms and scientific revolutions where the concepts of the background framework form a network of nodes with links between them that changes over time.

⁴ Sternberg (2003, 126–27) has a similar tripartite typology with further subdivisions. The difference between exploratory and transformational creativity is also implicit in the two levels of the more experiment-focused “4-space model of scientific discovery” (Schunn and Klahr 1995). A more detailed catalogue of typologies of creativity can be found in Sawyer (2012, 123–24) but for present purposes, the important observation is that many of them resemble Boden's typology. Thus, though paradigm theory is here related specifically to Boden's typology, this reflects a more general connection between Kuhn and the creativity literature and not merely a connection to elements that are idiosyncratic to Boden. It might also be added that Gaut and Kieran (2018b, 5) argue that “Boden's account is the most influential typology to be found in the contemporary philosophical literature.”

⁵ See Novitz (1999) for a discussion of the possibility of creativity that is independent of any conceptual space.

⁶ Despite being explicated in terms of a *conceptual* space, explorational creativity in science can arguably be both theoretical and experimental (see Klahr and Dunbar 1988). The same is the case for transformational creativity, for instance through “exploratory experiments” (Steinle 1997, 70).

Boden primarily introduces conceptual spaces through examples, and she does not, therefore, furnish these conceptual spaces with more explicit details; perhaps because the account is meant to be so general that it can cover creativity in most domains. Explicating Boden's conceptual spaces in the context of scientific creativity through paradigms – either following Kuhn's original exposition or later sophistications such as that offered by Thagard – can therefore be helpful. Arguably, also Kuhn relies heavily on examples, but his explication of paradigms in terms of a disciplinary matrix does provide additional details on the elements that direct thinking within a paradigm and consequently, also, more concrete suggestions for the dimensions in which one can go beyond a paradigm (as discussed in section 3). Thagard's (1992, chap. 2) conceptual systems account, in turn, offers more details on how conceptual spaces in science may be structured as concepts connected by kind-, instance-, rule-, property-, and part-links.

In the conceptual systems framework, exploratory creativity can then be identified as additions to the conceptual system that leaves the conceptual system (mostly) intact, arguably what Thagard describes as “[s]imple conceptual reorganizations that involves mere extension of existing relations” as opposed to “the revisionary sort [...] which involves moving the concepts around in the hierarchies and rejecting old kind-relations or part-relations” (Thagard 1992, 36–37). To use one of Thagard's (1992, 35) examples for such simple reorganizations, one can imagine the proposal to add a kind-link between the concept ‘dolphin’ and the concept ‘whale.’ If these were simply previously conceived as unrelated sea-creatures, adding this link would leave the remaining conceptual system intact, and the proposal would therefore qualify as exploratory creativity. With this connection to Thagard's conceptual systems, we can better understand why such exploratory creativity nevertheless “changes the map it inherits,” as Boden puts it above. The kind-link to whales embeds dolphins in a part of the conceptual system that includes for instance the part-link between spleens and whales (Thagard 1992, 35). Our expectations regarding dolphins, “the map,” will change – we now, for instance, expect dolphins to have spleens – even though the conceptual space as captured by the conceptual system remains the same apart from the added kind-link.⁷

Relating conceptual spaces to Kuhnian paradigms and, as Boden also does, exploratory creativity to the puzzle solving of normal science is perhaps especially interesting for the way it informs the practice that produces exploratory creativity. As also mentioned by Nickles above, Kuhn argues that discoveries through normal science are only possible because the paradigm requires “focusing attention upon a small range of relatively esoteric problems” (Kuhn 1970, 24). Thus, understanding conceptual spaces and exploratory creativity through Kuhn not only echoes Boden's argument that ideas can be creative despite preserving the conceptual space but adds that exploratory creativity might actually be aided the more convergent the thinking is. In more general terms, Kuhn's detailed account of normal science can offer a template for exploratory creativity that goes beyond Boden's generic remarks about

⁷ See Boden (2018) for other examples of exploratory, transformational, and combinational creativity in biology.

exploring the existing conceptual space. Furthermore, appreciating that the exploratory and largely convergent normal science can qualify as creativity rejects – as Kuhn also does – the conception that genuine creativity must be so radically divergent⁸ that it is restricted to paradigm shifts whose associated incommensurability is prone to reproduce the unfortunate view of creativity as inscrutable and unlearnable.⁹ Relatedly, the construal of normal science as creativity serves to break the linkage between scientific creativity and the scientific genius.¹⁰

Transformational creativity is the second more radical form of creativity that Boden identifies, and it includes instances that “involve someone’s thinking something which, with respect to the conceptual spaces in their minds, they *couldn’t* have thought before. The supposedly impossible idea can come about only if the creator changes the preexisting style in some way” (Boden 1991, 6). Explicating conceptual spaces in science as paradigms following the above, ideas exemplify transformational creativity if they cannot be subsumed under the current paradigm and thus go beyond normal science. As Boden argues, such ideas would inevitably require the creator to have altered the preexisting style and transformational creativity in science therefore comes with changes to the paradigm. This connects transformational creativity with the second type of creativity that Nickles finds implicit in Kuhn’s paradigm theory which precisely involves proposals for “a new defining framework.” According to Nickles’ Kuhn, this mode of creativity is characteristic of the revolutionary science that leads up to a paradigm shift. In associating paradigm shifts with transformations of a *conceptual* space, i.e. in bringing together Boden and Kuhn, one might in turn reinforce Nickles’ point that “a paradigm shift does not typically result from a massive infusion of new empirical results. Rather, it amounts to a conceptual reorganization of the old materials” (Nickles 2011, 212). This is also in accordance with a construal of transformational creativity in Thagard’s conceptual systems account as “*conceptual* revolutions” that “involve a dramatic replacement of a substantial portion of the conceptual system” (Thagard 1992, 32), which goes beyond adding or deleting single nodes or links, as in the dolphin example.

The association between transformational creativity and scientific revolutions, however, also emphasizes Boden’s claim that transformational creativity – with its requirement to think the unthinkable – is particularly challenging. Kuhn occasionally discusses paradigms as defining “the legitimate problems and methods of a research field” (Kuhn 1970, 10), but this arguably assumes an outsider perspective to the paradigm. A practitioner immersed in a paradigm will not come up with various

⁸ That convergent thinking is important for creativity is also corroborated by recent empirical findings (e.g. Cropley 2006; Webb et al. 2017; Zhu et al. 2019).

⁹ See Gaut (2014) for a more detailed discussion and rejection of the view that creativity cannot be taught. Indeed, the view implicit here is that there are teachable rationales in the context of discovery, a view that Nickles (e.g. 2006) has been a primary proponent of. This remark, however, does not entail an endorsement of for instance Simon’s (1973) proposal that creativity in science is entirely algorithmic.

¹⁰ See for instance Weisberg (1986) and Simonton (2013) for more on creativity and genius and how they come apart.

ideas and then compare them to the paradigm to decide which are legitimate. Rather, such a practitioner will rarely if not never think anything that violates the paradigm; as also alluded to by Kuhn (e.g. 1970, 93).¹¹ The practitioners within a paradigm are, as Margolis finds, entrenched in particular “habits of the mind” (Margolis 1993, 22) which will typically take the form of “intuitions that seem too obviously right to prompt discussion” (Margolis 1990, 434). Indeed, the practitioners are so engrossed in the paradigm that the first challenges to transformational creativity are to realize that transformational creativity is even possible and to become aware what transformational creativity might change. The teaching of paradigm theory and scientific revolutions will illustrate that transformational creativity in science is both possible and historically actual. Together, they provide for the realization that the scientific practice with its foundational principles and assumptions is not fixed but rather an additional arena for scientific innovation beyond normal science. Section 3 will expand on this theme focusing on how Kuhn’s disciplinary matrix can be seen as introducing a subdivision among types of transformational scientific creativity and thus as giving more details for what might change with transformational creativity.

Boden’s third type of creativity involves “making unfamiliar combinations of familiar ideas” (Boden 1991, 3).¹² This *combinational* creativity is for instance exemplified by a collage (Boden 1991, 3), and an example from physics is the integration of the theories of electric and magnetic phenomena into electromagnetism in the nineteenth century. Boden insinuates that combinational creativity is less surprising – and thus less creative – than exploratory and transformational creativity. However, Kuhn’s account of the workings of paradigms proposes a very different verdict in the context of science. As also alluded to above, Kuhn finds it an important role of paradigms that they set the type of problems that practitioners within the paradigm can (imagine to) work on and what can be considered acceptable solutions including the type of resources that one can draw upon. On this view, the combination of elements of multiple paradigms is therefore rarely, if not never, set as a puzzle for normal science. Thus, new ideas that do so – instances of combinational creativity – will arguably be more surprising than at least exploratory creativity from the perspective of normal science. In science, following Kuhn, a challenge therefore lies in identifying, let alone solving, problems that could be approached through combinational creativity. Indeed, such combinational creativity might be beyond the assessment and even the recognition of any one paradigm whereby such ideas would appear to the practitioners of the paradigms to be not worth entertaining. If one adopts Kuhn’s (1970, chap. 10) view that paradigms are often incommensurable,¹³ combinational creativity could even be outright impossible in some circumstances since it would be embedded in two different worlds at once. Thagard (1992), in contrast, argues that paradigms are not in general incommensurable (see also, e.g., Szumilewicz 1977; Devitt 1979). Indeed, Thagard’s conceptual systems

¹¹ Kuhn argues that extra-paradigmatic ideas will only occur through “something’s first going wrong with normal research” (Kuhn 1970, 114); for instance the accumulation of anomalies.

¹² See Thagard and Stewart (2011) for an interesting neural model of combinational creativity.

¹³ It should be noted that Kuhn continued to refine and modify the incommensurability thesis in reaction to this critique (Hoyningen-Huene 1990; Demir 2008; Sankey 2019). There may therefore be versions of it that are more hospitable to combinational creativity.

are more hospitable to the possibility that two previously unrelated conceptual systems become connected by a new link whose introduction would therefore qualify as combinational creativity.

Where exploratory creativity and transformational creativity maps distinctions already made by Kuhn in the context of paradigm theory, combinational creativity is at odds with at least Kuhn's account of paradigms. The meeting of combinational creativity and paradigm theory therefore offers an interesting occasion to consider whether creativity in science is different from creativity elsewhere: Where Boden finds that combinational creativity is generally less surprising and rather common, there are perhaps special obstacles to it in science which will make combinational scientific creativity rarer and more challenging. Relatedly, Boden's account can also be used as an occasion to discuss Kuhn's view that paradigms are incommensurable and to consider whether the combination of paradigms is possible.

3 The disciplinary matrix and transformational creativity

Transformational creativity is particularly challenging, also in science. It requires thinking outside the box and though the box may be known through acquaintance with the paradigm, the outside will remain unknown. This section, however, will argue that Kuhn's disciplinary matrix gives some details on the possible directions out of the box. The disciplinary matrix suggests what to think when one is looking for ideas that might qualify as transformational creativity and more can therefore be said about transformational creativity in science than "think the unthinkable." In the postscript to the second enlarged edition of *The Structure of Scientific Revolutions* (1970), Kuhn provides a – for that purpose – helpful explication of 'paradigm' in terms of what he calls the "disciplinary matrix": "'disciplinary' because it refers to the common possession of the practitioners of a particular discipline; 'matrix' because it is composed of ordered elements of various sorts" (Kuhn 1970, 182). Kuhn lists four such types of components of the disciplinary matrix: symbolic generalizations, models (broadly construed), values, and exemplars. Where awareness of the existence of a disciplinary matrix allows the insight that the disciplinary matrix could be different, i.e. that transformational creativity is possible, the ordering into types of components furnishes this insight with some indication of *what* might be different in other disciplinary matrices, i.e. some suggestion for the directions that transformational scientific creativity may take that goes beyond generic references to conceptual spaces as a whole. The components of the disciplinary matrix introduce, as such, a subdivision to transformational scientific creativity whereby creative ideas can be categorized according to the type of component of a disciplinary matrix that it modifies or rejects. This once again illustrates the synergies of integrating this typology of creativity with paradigm theory.

Kuhn describes symbolic generalizations as "the formal or the readily formalizable components of the disciplinary matrix" (Kuhn 1970, 182). Kuhn gives Newton's second law, $F = m \cdot a$, as an example of the former and Newton's third law, "action equals reaction", as an example of the latter (Kuhn 1970, 183). Due to their formal nature, attempts at transformational creativity could apparently proceed by simply

changing, for instance, a multiplication into an addition in one of the central symbolic generalizations. However, arbitrary changes to the symbolic generalizations will most often not generate new disciplinary matrices but rather generate defective or outright inconsistent groupings of formal(izable) statements. To be creative ideas rather than incomprehensible nonsense, changes to the symbolic generalizations must be subtle, and this applies to all transformational creativity. “Unless someone realizes the structure which old and new spaces have in common, the new idea cannot be seen as the solution to the old problem. Without some appreciation of shared constraints, it cannot even be seen as the solution to a new problem intelligibly connected with the previous one” (Boden 1991, 96–97). Kuhn, as Nickles observes, makes the similar observation that “if a particular move is too divergent, it risks not being recognized as a serious constructive contribution to that field” (Nickles 2011, 211–12).¹⁴ Importantly, this implies that it is inconceivable to replace all aspects of the paradigm at once. Even in cases of dramatic conceptual changes, it is necessary that “continuity is maintained by the survival of links to other concepts” (Thagard 1992, 32; see also Nersessian 1987; Chen and Barker 2000). In early quantum mechanics, for instance, the Hamiltonian for the hydrogen atom underwent several changes to accommodate the motion of the nucleus, the spin-orbit coupling, and relativistic effects (Kragh 2003). Much of the framework surrounding this central symbolic generalization was preserved under each change even though especially the addition of relativistic effects could be considered the first move towards the new disciplinary matrix of relativistic quantum mechanics. While emphasizing that transformational creativity must be subtle may reinforce the impression that transformational creativity is difficult, it also importantly signifies that transformational creativity is not facilitated by being as radical as possible.

The second type of elements in the disciplinary matrix is models. This includes the ontological models of the disciplinary matrix such as “heat is the kinetic energy of the constituent parts of bodies” (Kuhn 1970, 184), but also models of a more heuristic character such as “the molecules of a gas behave like tiny elastic billiard balls in random motion” (Kuhn 1970, 184). Transformational creativity through new heuristic models might be exemplified by the introduction of the liquid drop model of the atomic nucleus (see, however, Andersen 1996, 472). Transformational creativity through new ontological models would involve changes to what we assume exists, such as the proposal to replace phlogiston for oxidation, or changes to how the already existing relate to each other, exemplified by Copernicus’ heliocentrism. Thagard (1992, 191–99) gives the more detailed account of the Copernican revolution as a conceptual change to the kind-links of the conceptual system as exemplified by the Sun and the Moon no longer belonging to the kind ‘planet’.

Values form the third type of element in the disciplinary matrix. According to Kuhn, these tend to be more widely shared between disciplinary matrices. But changes of values can, nevertheless, qualify as transformational creativity, though the potential for creativity in this part of the disciplinary matrix is consequently

¹⁴ Indeed, paradigm theory might inform the conditions for when divergent thinking is advisable in science.

more limited. Kuhn proposes the value of prediction – and generally empirical significance – as central to many scientific disciplines, but other examples include accuracy, simplicity, and self-consistence (Kuhn 1970, 185). Knowledge of the current operative values and the recognition of the role of values in the disciplinary matrix enable proposals to remove or include values to the disciplinary matrix, or to prioritize the values differently. Sabine Hossenfelder (2018), for instance, argues that the emphasis on the values of beauty, simplicity, and naturalness leads contemporary physics astray which can at least be regarded as the proposal to prioritize accuracy and prediction over these. The introduction of new values might be exemplified by Richard Dawid's (2013) proposal that “non-empirical confirmation” should help adjudicate between theories in quantum gravity research. Since the empirical consequences of these theories are very limited, they are hardly encompassed by the “classical empirical paradigm” (Dawid 2013, 22), and Dawid might in this light be construed as proposing a transformation to the disciplinary matrix through new values that allow these theories to be included and compared.

From the perspective of transformational creativity in science, the recognition that such creativity can concern both models and values rejects the view that scientific discovery – especially its significant changes – must proceed through new equations. Connecting transformational scientific creativity with the disciplinary matrix can therefore broaden the search space for new creative ideas. More generally, this connection provides the first step towards thinking outside the box by indicating what might be different outside. The types of components of the disciplinary matrix can indicate this by suggesting that the symbolic generalizations, models, and values might be different and therefore be subject to change through transformational creativity.

4 Teaching scientific creativity

To teach the tripartite typology of creativity in a philosophy of science course, one can largely follow one's preferred approach to teaching paradigm theory. However, to emphasize that normal science is creative, it may be helpful to stress the way paradigms constrain normal science without giving its problems or solutions explicitly. The close connection between normal science and exploratory creativity can then be used as a starting point for introducing Boden's typology. Having already introduced paradigms in the teaching of paradigm theory, combinational creativity can be explicated as the meeting of paradigms, though it may here be relevant to add a discussion of the apparent conflicts between combinational creativity and the (alleged) incommensurability of paradigms. Transformational creativity and the way it breaks with the existing conceptual space can in turn be explained as the departure from the current paradigm perhaps emphasizing the further subdivisions within transformational creativity that Kuhn's disciplinary matrix provides for.

While the teaching of scientific creativity can, as such, be integrated with most approaches to teaching paradigm theory, I favor the case based active learning approach to teaching philosophy of science¹⁵ (Green et al. 2021) and Cabrera's "Second Philosophy" approach, which consists, roughly, in emphasizing the concrete ways in which philosophical problems arise during scientific practice" (Cabrera 2021, 2), both discussed in further detail elsewhere in this topical collection. In combination, they propose an approach where episodes from the history of science and typical circumstances from the scientific practice are used as generators and motivation for the philosophical discussions. I shall here briefly illustrate this approach with three cases/exercises from my own teaching that attempt to integrate paradigm theory and scientific creativity.

4.1 Exploratory creativity/normal science

Neptune was telescopically discovered in 1846 after mathematical astronomers had predicted where to point the telescope. The prediction was based on the errant motion of Uranus which only satisfied Newton's theory of gravity if there existed a hitherto undiscovered 8th planet with a certain orbit around the sun (see, e.g., Sheehan et al. 2021). The discovery of a planet very much lends itself to Boden's metaphor for exploratory creativity of discovering "unexpected locations" on the map of our "home-territory." The map, in this case, is based on the Newtonian paradigm, and one way of working with this case study is having the students discuss in groups how the discovery of Neptune fits into this paradigm (as it is, for instance, summarized by Ladyman (2002, 98–100)). This serves to substantiate Boden's map metaphor and thus how exploratory creativity play out relative to a conceptual space. From the perspective of paradigm theory, the case illustrates how the study of esoteric details in normal science is the basis for new scientific discovery, the discovery of Neptune relying on precision measurements of the motion of Uranus, detailed star charts, advanced perturbative methods in celestial mechanics, to name some. More advanced students can be given these to reproduce the prediction themselves (using numerical simulations).

4.2 Transformational creativity

The discovery of Neptune – brought about by convergent thinking – stands in contrast with the more divergent thinking involved in ideas that go beyond established paradigms. Section 3 gave several examples of this, and Thagard's examples of conceptual revolutions as well as Kuhn's examples of paradigm shifts can also serve as cases that illustrate this difference. However, for purposes of illustrating transformational creativity, one can consider choosing a case that also emphasizes how transformational creativity is more than new equations, how such creativity must be subtle to be recognized as a promising new idea, and how it involves thinking the unthinkable. Copernicus' heliocentrism nicely exemplifies all. As mentioned

¹⁵ This approach of course shares features with integrated history and philosophy of science which is often already central to the teaching of paradigm theory (Mauskopf and Schmaltz 2012).

above, it primarily involves a change in the ontological model. Its subtlety lies in its preservation of the methods and principles of Ptolemy's astronomy (Thagard 1992, 193–99) as well as in being worked out in similar mathematical detail which made Copernicus' proposal stand out compared to earlier gestures towards heliocentrism (Shank 2017). Finally, Copernicus had to realize and convince others that the Earth's immobility could be an illusion (Chen-Morris and Feldhay 2017). Students can, for instance, work with this case study by adding these details about methods, principles, mathematics, and preconceptions to Thagard's (1992, fig. 8.2-8.3) diagrams of the respective conceptual systems of Ptolemy and Copernicus and discuss how the former transforms into the latter.

4.3 The disciplinary matrix

This exercise asks students to consider the disciplinary matrix of their own scientific (sub)discipline using the types of components discussed in section 3. The purpose of the exercise is to indicate that also contemporary science operates within a paradigm and that the content of this paradigm can be organized by the disciplinary matrix. This, in turn, raises the awareness that there is a potential for transformational creativity even in contemporary science along the dimensions exemplified in section 3. Immediately filling in the disciplinary matrix can be difficult for students, but it can be facilitated by asking (1) whether there are principles (or laws) that any serious scientific theory must satisfy which is helpful for teasing out the paradigm's symbolic generalizations and ontological models; (2) what scientific theories should aim for which gets at the values of the paradigm; and (3) how they imagine the systems being studied which can be a way of realizing what heuristic models that are operative. If the gained understanding of the contemporary disciplinary matrix is in turn supplemented by analyzing historical examples of transformational creativity – like those given in section 3 – through the lens of the types of components of the disciplinary matrix, then one might hope that these types of components can work as tools for the students with which to identify possible venues for transformational creativity in the current disciplinary matrix.

By explicating Boden's conceptual spaces as paradigms, paradigm theory can be used in philosophy of science courses to introduce to students the influential distinction in the literature on creativity between exploratory, transformational, and combinational creativity as it applies in a scientific context. Even though this merely introduces them to a categorization of creativity, it provides for several synergies with paradigm theory, as indicated, that illuminate important aspects of paradigm theory and the typology of creativity alike. Furthermore, it may contribute to the aim of Cabrera's second philosophy approach to address the challenge identified by Lederman (1992) in the context of the teaching of nature of science that students fail "to appreciate the social, creative, and imaginative elements of science" (Cabrera 2021, 10).

One issue, however, remains: How does one generate these creative ideas and relatedly, how can we teach this? The restraints of paradigms make such questions particularly pressing for transformational creativity, but similar questions can also

be raised for exploratory and combinational creativity. While for instance Thagard's (1992, 35) list of changes a conceptual system can undergo indicates *what* a creative idea might do, i.e. what kind of idea to look for, it gives little instruction for *how* to look. Likewise, the disciplinary matrix indicates *what* transformational creativity might change, but not *how* to come up with such creative ideas. As argued above, Kuhn's account of normal science, if true, may suggest a particular mode of research – the focusing on esoteric details – that can facilitate exploratory creativity, but as a whole the question about the generation of creative ideas exposes some limitations to the teaching of scientific creativity through paradigm theory. These limitations are well captured by Nancy Nersessian's (e.g. 1999) distinction between a product and process approach to the study of scientific creativity and discovery (see also Thagard 2012, pt. III). Nersessian's own work on conceptual change is exemplary of the process approach since it explores "the *methods* or kinds of *reasoning* through which concepts are constructed" (Nersessian 1999, 6), whereas she mentions Kuhn as an example of the product approach that emphasizes the results of such methods and reasoning. This product approach is also reflected in the discussions here where creativity was categorized based on the kind of surprise the creative *product* gave rise to relative to a conceptual space which was in turn explicated by paradigms or conceptual systems. Thus, in focusing on typologies for creativity and paradigm theory, important themes from the process approach are therefore neglected such as model-based reasoning in general and the development of mental models in particular (see, e.g., Magnani, Nersessian, and Thagard 1999; Magnani and Casadio 2016). When teaching creativity, it would therefore be ideal to also teach for instance Nersessian's (e.g. 2008) work on how creative ideas can be generated through mental models such as analogy, visual modeling, and thought experiments.

5 Conclusion

Paradigm theory provides a good infrastructure for teaching scientific creativity and more particularly, Boden's influential tripartite typology of creativity. This distinction between combinational, exploratory, and transformational creativity can be explicated in a scientific context through Kuhn's account of paradigms and Thagard's related notion of conceptual systems. Combinational creativity combines elements from different paradigms, exploratory creativity explores the space already set by the paradigm, and transformational creativity characterizes ideas that go beyond any known paradigm. Paradigm theory thus functions as a framework with which to categorize and analyze scientific creativity that can be taught by simply adding a perspective when teaching paradigm theory. The integration of paradigm theory and scientific creativity is of mutual benefit. Kuhn's disciplinary matrix and Thagard's conceptual systems provide, in different ways, structure to Boden's conceptual spaces. Moreover, Thagard's conceptual systems can capture what happens to the conceptual space when new creative ideas are adopted. This includes the conceptual revolutions induced by transformational creativity, the connection of distinct conceptual systems in combinational creativity, and the expansion of such systems through exploratory creativity. Exploratory creativity can also be informed

by Kuhn's account of normal science, and a subdivision within transformational creativity is implicit in Kuhn's disciplinary matrix. The association between normal science and exploratory creativity in turn emphasizes that normal science – despite its description as “puzzle solving” – can be creative. This signifies, importantly, that scientific creativity is not limited to the big changes of scientific revolutions. Furthermore, the association between such scientific revolutions and a type of creativity that goes beyond a *conceptual* space can serve to emphasize that revolutions in science, as both Thagard and Kuhn point out, are often driven by conceptual changes. Finally, Boden's identification of a type of creativity that combines conceptual spaces suggests the possibility of combining paradigms, a notion that might be outright incomprehensible according to one reading of Kuhn. However, from Kuhn's account of normal science, we also get the qualification that combinational creativity in science is at least difficult – and probably more so than Boden indicates – since no paradigm will set such combination as one of its puzzles.

Paradigm theory and scientific creativity have, in other words, much to offer each other and the present proposal is therefore to cover scientific creativity as part of the discussion of paradigm theory in philosophy of science courses.

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