Specialisation By Value Divergence: The role of epistemic values in the branching of scientific disciplines

Matteo De Benedetto*and Michele Luchetti†

Preprint
Published in *International Studies in the Philosophy of Science*

Abstract

According to Kuhn's speciation analogy, scientific specialization is fundamentally analogous to biological speciation. In this paper, we extend Kuhn's original language-centered formulation of the speciation analogy, to account for episodes of scientific specialization centered around methodological differences. Building upon recent views in evolutionary biology about the process of speciation by genetic divergence, we will show how these methodology-centered episodes of scientific specialization can be understood as cases of specialization driven by value divergence. We will apply our model of specialization by value divergence to an episode of methodology-centered scientific specialization: the emergence of molecular biology.

1 Introduction

As highlighted by several scholars (cf. Bird 2000; Renzi 2009; Reydon and Hoyningen-Huene 2010; Wray 2011; Kuukkanen 2012), Kuhn's work is permeated by evolutionary analogies. From the analogy between scientific and evolutionary progress that closes *Structure* (Kuhn, 1962) to the niche-construction analogy central to "The Road Since Structure" (Kuhn, 1990), evolutionary theory is Kuhn's preferred analogical domain for describing the development of science. One of Kuhn's most innovative evolutionary analogies and, at the same time, one of the least discussed, is the so-called speciation analogy (cf. Kuhn 1990), i.e., Kuhn's understanding of the increasing specialization of science as somewhat analogous to the process of biological speciation.

In this work, we will explicate Kuhn's analogy between scientific specialization and biological speciation in the light of contemporary philosophy of science

---

*Ruhr-Universität-Bochum, Institut für Philosophie II; matteo.debenedetto@rub.de.
†Max-Planck Institute for the History of Science, Berlin; mluchetti@mpiwg-berlin.mpg.de.

and evolutionary biology. More specifically, we will extend Kuhn's analogy in order to adequately account for episodes of scientific specialization centered around methodological differences between scientific communities. If, in fact, Kuhn's original account of scientific specialization focuses exclusively on lexical differences between scientific disciplines, contemporary philosophy of science has shown that several episodes of scientific specializations do not primarily involve language differences, but rather differences in methodology.[1] In order to extend Kuhn's speciation analogy to these methodology-centered episodes of scientific specialization, we will build on recent findings in evolutionary biology that highlight how biological speciation might occur also in the absence of physical barriers, thanks to the combination of niche-constructing activities of organisms and of genetic divergence. In analogy with these episodes of biological speciation by genetic divergence, we will argue that methodology-centered episodes of scientific specialization can be understood as episodes of specialization by value divergence. That is, in these episodes, the methodologies of two groups within a given scientific community progressively grow apart due to the combination of their epistemic niche-constructing activities and a positive feedback-loop mechanism between the values embedded in a group's disciplinary matrix and the group's worldview. We will show the adequacy of our extended speciation analogy by reconstructing as an instance of specialization by value divergence a case of methodology-centered scientific specialization, i.e., the emergence of molecular biology.

Our aim in this paper will be two-fold. First, we will extend Kuhn's speciation analogy in the light of recent views in evolutionary biology to account for the diversity of scientific specializations. Secondly, by doing that, we seek to highlight the crucial, yet often underappreciated role that epistemic values play in the branching of scientific disciplines.

In Section 2, we will analyze Kuhn's analogy between biological speciation and scientific specialization in its original formulation. In Section 3, we will focus on the limits of Kuhn's language-centered speciation analogy, in so far as history and philosophy of science have recently highlighted that several episodes of scientific specialization seem to be centered around methodological differences, rather than language differences. In Section 4, we will present recent findings in evolutionary biology that show how biological populations can undergo speciation also in the absence of physical barriers thanks to the process of genetic divergence. In Section 5, we will argue that biological speciation by genetic divergence offers us a blueprint for extending Kuhn's speciation analogy to methodology-centered episodes of scientific specialization. We will first show how to model these episodes of specialization as driven by value divergence and, then, we will apply our model of specialization by value divergence to a case study: the emergence of molecular biology. Section 6 concludes.

---

[1] See, for example, (Rheinberger, 1997; Solomon, 2001; Chang, 2012, 2013; Shan, 2020b).

2 Kuhn's Speciation Analogy and the Branching of Scientific Disciplines

In this section, we will focus on Kuhn's speciation analogy, i.e., the evolutionary analogy that Kuhn (Kuhn, 1990) draws between biological speciation and scientific specialization. More specifically, by the speciation analogy, we refer to Kuhn's thesis that the process of increasing specialization that scientific disciplines exhibit in the growth of scientific knowledge is fundamentally analogous to the process of speciation that biological populations undergo as a result of natural selection. Kuhn presents this analogy with the following words:

> "After a revolution there are usually (perhaps always) more cognitive specialties or fields of knowledge than there were before. Either a new branch has split off from the parent trunk, as scientific specialties have repeatedly split off in the past from philosophy and from medicine. Or else a new specialty has been born at an area of apparent overlap between two preexisting specialties, as occurred, for example, in the cases of physical chemistry and molecular biology. (. . .) Over time a diagram of the evolution of scientific fields, specialties, and subspecialties comes to look strikingly like a layman's diagram for a biological evolutionary tree. (. . .) revolutions, which produce new divisions between fields in scientific development, are much like episodes of speciation in biological evolution. The biological parallel to revolutionary change is not mutation, as I thought for many years, but speciation. And the problems presented by speciation (e.g., the difficulty in identifying an episode of speciation until some time after it has occurred, and the impossibility, even then, of dating the time of its occurrence) are very similar to those presented by revolutionary change and by the emergence and individuation of new scientific specialties. (Kuhn, 1990, pp. 98-99)

The proliferation of scientific disciplines is for Kuhn the natural consequence of scientific progress, just like the proliferation of different species of organisms is a byproduct of biological evolution. The fragmentation of scientific knowledge in a plethora of specialized disciplines is not a temporary, contingent element of science, as many proponents of the unity of scientific knowledge seem to assume, but a permanent, necessary feature of scientific development. The more science progresses, the more it fragments itself. Since scientific progress amounts, for Kuhn, to the ever-increasing problem-solving capacity of science, the evolutionary-like process of adaptation and selection of scientific knowledge determines a proliferation of domain-specific scientific disciplines optimally adapted to the specific problems they ought to solve. This progress-driven specialization effect of scientific development is a sort of "principle of divergence" (Darwin, 1859) for scientific knowledge that is encoded in Kuhn's speciation analogy. According to Darwin, natural selection causes competitors to evolve to become more dissimilar from each other in resource use and associated traits, which explains the process of speciation in terms of natural selection. Analogously, the branching of scientific disciplines is explained, by Kuhn, as a result of diverging epistemic selective pressures.

Kuhn's speciation analogy, together with its epistemic justification of scientific specialization, plays a crucial role in Kuhn's late philosophy of science, as it dovetails with two fundamental pillars of Kuhn's thought: the non-teleological nature of scientific progress and the role of incommensurability in science.

We mentioned above how Kuhn understands scientific specialization as an epistemic byproduct of scientific progress. Science progresses through the development of increasingly specialized (sub)disciplines optimally adapted to solve a specific set of significant problems. In Kuhn's view, this proliferation of scientific disciplines shows that the only viable notion of progress in science is a non-teleological one (cf. Kuukkanen 2021; Haufe 2022). Just like the Darwinian explanation of the proliferation of biological species as a consequence of the process of natural selection, i.e., Darwin's aforementioned principle of divergence, constituted one of the major arguments against teleological notions of progress in biology, scientific specialization shows, for Kuhn, that teleological notions of scientific progress are doomed to fail. The ever-increasing diversity and fragmentation of scientific knowledge pushes us, in fact, to acknowledge that, as Kuhn has stressed since *Structure*, there is no unique goal nor end to scientific inquiry. The only kind of directionality that one can see in the history of science is a backward one, i.e., a progress from something, not a progress towards something.

In addition to clarify the non-teleological nature of scientific progress, Kuhn's speciation analogy plays another important function in Kuhn's mature philosophy of science, that is, it shows the positive role of incommensurability in scientific practice. Despite post-Kuhnian philosophy of science has overwhelmingly focused on the negative effect that the phenomenon of incommensurability might have for our notions of scientific rationality and realism,[2] Kuhn understood incommensurability as a positive force in the development of scientific knowledge (cf. Kuhn 1970, 1974, 1983a, 1989, 1990, 1993). Specifically, incommensurability denotes the division between the practice and the language of different scientific communities that is necessary for them to make progress with respect to the specific problems that they set themselves to solve. Just like different biological populations often need a certain degree of isolation in order to evolve optimal adaptations to particular environmental pressures, so do, according to Kuhn, scientific communities have to be isolated, to a certain degree, in order to successfully practice their specialized trades:

> "The second parallel between biological and scientific development (. . .) concerns the unit which undergoes speciation (not to be confused with a unit of selection). In the biological case, it is a reproductively isolated population, a unit whose members collectively embody the gene pool, which ensures both the population's self-perpetuation and its continuing isola-

---

[2] Examples of critical discussion of incommensurability as a threat to scientific rationality and realism are (Shapere, 1966; Lakatos and Musgrave, 1970; Stegmüller, 1976; Lakatos, 1978; Kitcher, 1978; Laudan, 1981; Psillos, 1999; Friedman, 2001).

> tion. In the scientific case, the unit is a community of intercommunicating specialists, a unit whose members share a lexicon that provides the basis for both the conduct and the evaluation of their research and which simultaneously, by barring full communication with those outside the group, maintains the isolation from practitioners of other specialties. To anyone who values the unity of knowledge, this aspect of specialization – lexical or taxonomic divergence, with consequent limitations on communication – is a condition to be deplored. But such unity may be in principle an unattainable goal, and its energetic pursuit might well place the growth of knowledge at risk. Lexical diversity and the principled limit it imposes on communication may be the isolating mechanism required for the development of knowledge. Very likely it is the specialization consequent on lexical diversity that permits the sciences, viewed collectively, to solve the puzzles posed by a wider range of natural phenomena than a lexically homogeneous science could achieve. (Kuhn, 1990, pp. 105-106)

Kuhn's speciation analogy shows that incommensurability is not a danger to scientific progress, but one of its epistemic preconditions. As explicitly stressed by more recent theories that build upon Kuhn's account of scientific specialization, incommensurability drives the improvement of scientists' conceptual tools (cf. Wray 2011) and helps to isolate scientific communities from non-epistemic pressures (cf. Haufe 2022). The increase of problem-solving capacity that the history of science displays is then possible also thanks to the lack of perfect communication and conceptual overlap between different scientific disciplines, i.e., thanks to incommensurability.

In this way, Kuhn's speciation analogy clarifies how the development of scientific knowledge is an evolutionary process and further specifies the nature and the role of scientific progress and incommensurability in Kuhn's mature philosophy of science. It does that by providing an epistemic justification for scientific specialization that understands specialization as a necessary condition for the characteristic progressive nature of scientific knowledge.

3 More than Language: methodological incommensurability between scientific disciplines

We saw in the last section how Kuhn's speciation analogy clarifies the positive role that the phenomenon of incommensurability plays in scientific development, namely, that of providing the necessary degree of isolation that fuels the initial development of a new scientific discipline. In this section, we will look more closely at this isolation-inducing role of incommensurability in scientific specialization and, more specifically, at the specific kinds of incommensurability that can be responsible for this phenomenon.

Kuhn, in presenting his speciation analogy, explicitly focuses on a specific kind of incommensurability, namely, what is usually referred to in Kuhn scholarship as taxonomic incommensurability (Sankey, 1997), i.e., the kind of local intranslatability of kinds between different scientific disciplines or theories. Taxonomic incommensurability is the last version of Kuhn's semantic incommensurability (or meaning incommensurability), i.e., the dimension of incommensurability that sees this phenomenon as a linguistic phenomenon that denotes differences in meaning between (parts of) different scientific theories.[3] This semantic understanding of incommensurability, which Kuhn employs in his speciation analogy, is a byproduct of a more general linguistic change in Kuhn's late philosophy. As stressed by several Kuhn scholars (cf. Bird 2002; Shan 2020a), in his post-*Structure* years Kuhn's philosophy underwent a lexical turn that caused him to explicate all the central notions of his philosophy (e.g., paradigm, revolution, incommensurability, ...) linguistically. Even Kuhn's notion of incommensurability, a notion that had a clear multifaceted character in *Structure*, is reduced only to his semantic dimension by the late Kuhn (cf. Sankey 1993; Marcum 2015). Thus, as we saw in the second quote of the previous section, when describing the speciation-like process that underlies the branching of scientific knowledge, Kuhn stresses the role of lexical diversity and the consequent partial linguistic isolation driving the detachment of the soon-to-be new scientific discipline from the discipline of origin.

Despite Kuhn's explicit focus on semantic incommensurability, we could ask whether lexical diversity alone exhausts the role that incommensurability plays in scientific specialization. After all, Kuhn's linguistic turn has been criticized for being mostly driven by personal motivations, such as Kuhn's desire to be understood and appreciated by the philosophers of science of his time, and for eliminating some of the most original and forward-looking innovations of *Structure* (cf. Bird 2002; Shan 2020a). Moreover, scientific specialization is an ubiquitous phenomenon in the history of science and, as such, we can expect it to take many forms and to be determined by a plethora of internal and external factors. It thus seems extremely likely that there is more than language barriers behind the incommensurability-driven speciation of scientific disciplines. As a matter of fact, recent scholarship has explicitly questioned the adequacy of Kuhn's semantic focus on the specialization of scientific disciplines, showing how in the recent history of science we can find several examples of specialization that do not seem to revolve around linguistic barriers between the disciplines. Examples of scientific specializations that have been claimed not to revolve around semantic incommensurability include the birth of statistical mechanics (Politi, 2019), the development of molecular biology (Politi, 2018), and the emergence of evolutionary paleontology (Haufe, 2022). In these examples, the differences between the scientific (sub)community developing the new scientific discipline and the community of origin do not seem to revolve around differences in language, but rather around differences in problems, methods, and standards.

Problems, methods, and standards are important components of the other

---

[3] The exact distinction between different kinds of incommensurability is a subject of contention among Kuhn scholars (cf. Sankey 1994; Hoyningen-Huene 1993; Hoyningen-Huene and Sankey 2001; Oberheim and Hoyningen-Huene 2018). Here we blur certain distinctions between different versions of semantic incommensurability in order to focus instead on the difference between semantic kinds and methodological kinds of incommensurability.

main dimension of Kuhn's original, multifaceted notion of incommensurability, namely, what is usually called methodological incommensurability (cf. Sankey 1994; Hoyningen-Huene and Sankey 2001; Oberheim and Hoyningen-Huene 2018). Methodological incommensurability denotes the differences in methods and methodology between different scientific communities. In *Structure*, Kuhn discusses at length this dimension of incommensurability, stressing that the impossibility of a final proof between competing paradigms is also a byproduct of the methodological differences in the problems, methods, standards, values, and commitments between scientists working within different paradigms:

> "Through the theories they embody, paradigms prove to be constitutive of the research activity. They are also, however, constitutive of science in other respects, and that is now the point. In particular, our most recent examples show that paradigms provide scientists not only with a map but also with some of the directions essential for map-making. In learning a paradigm the scientist acquires theory, methods, and standards together, usually in an inextricable mixture. Therefore, when paradigms change, there are usually significant shifts in the criteria determining the legitimacy both of problems and of proposed solutions." (Kuhn, 1962, p. 114)

Given the significance that Kuhn attributes to methodological incommensurability in *Structure*, it is not surprising that the aforementioned examples of scientific specialization without semantic incommensurability involve incommensurable methodologies. Politi (Politi, 2019) argues, in fact, that both specialization processes behind the birth of statistical mechanics and molecular biology involve important differences in methods, while Haufe (Haufe, 2022) explains that the emergence of evolutionary paleontology as a scientific discipline involves substantial differences in problems and methods between the soon-to-be community of evolutionary paleontologists and their community of origin. Indeed, all these three examples of scientific specialization can be considered as examples of specialization centered around methodological incommensurability.

Epistemic values are an important component of the practice of a scientific community that is not explicitly conceptualized in these three examples of methodology-centered scientific specialization. Yet, epistemic values play a crucial role in Kuhn's notion of methodological incommensurability, in that they represent the core standards of evaluation guiding the epistemic choices of a scientific community (cf. Kuhn 1970, 1977; Sankey 1994; Hoyningen-Huene and Sankey 2001). As such, despite epistemic values do not strictly speaking belong to the methodological components of a scientific practice, they are an important part of the disciplinary matrix of a scientific community that is intertwined with its methodology. We could then ask what role these epistemic values play in these methodology-centered episodes of scientific specializations. This question is independently justified also by the pervasive influence that epistemic values have on several aspects of scientific practice closely connected to specialization, such as theory choice (McMullin, 1983; Sankey, 1995; Okasha, 2011), theory development (Laudan, 1984, 2004), scientific rationality (Longino, 1990; Lacey, 1999; Solomon, 2001; Douglas, 2009; Carrier, 2013), and scientific progress (Laudan, 1978). Moreover, recent integrated history and philosophy of science has stressed the important role that epistemic values had in major disciplinary branchings in the history of science, such as the birth of modern chemistry (Chang, 2012, 2013), the origin of genetics (Shan, 2020b), and the emergence of empirical psychology (Feest, 2014).

Thus, the history of science seems to offer several examples of scientific specialization that were centered around methodological incommensurability, and in which differences in epistemic values arguably played a major role. In order to clarify the role of epistemic values in these episodes of specialization and to extend Kuhn's account of specialization to include these cases, we need first to go back to Kuhn's speciation analogy and extend it. In order to do that, we will borrow some conceptual tools from contemporary evolutionary biology.

4 Biological Speciation by Genetic Divergence

So far, we have closely followed Kuhn in discussing his analogy between the branching of scientific disciplines and biological speciation. Yet, as we saw in the last section, there seems to be more to the positive role of incommensurability in scientific specialization than the lexical isolation on which Kuhn focuses. Thus, in order to explicate the methodology-centered mechanism of specialization that we saw at work in the examples mentioned in Section 3, we need to go beyond Kuhn's original analysis. To do that, we will examine more in detail the mechanism of biological speciation in the light of recent developments in evolutionary biology. More specifically, we will focus on niche construction as an active mechanism involved in speciation and on genetic divergence as the driver of episodes of speciation that do not involve physical barriers. In the next section, we will show how analogous mechanisms are at work behind methodology-centered specializations in scientific practice.

The first aspect of biological speciation on which we will focus is the phenomenon of niche construction. Niche-construction theory is a branch of evolutionary biology that models evolutionary dynamics based on the evidence that organisms can fit the environment not only by evolving adaptations through natural selection, but also by transforming the environment during their lifespan (cf. Odling-Smee, Laland and Feldman 2003). Organisms do so, for instance, by regularly modifying local resource distributions, by choosing and changing habitats, or by constructing artifacts. These niche-constructing activities indeed emerge as responses to external selective pressures. At the same time, as depicted in Figure 1, these activities, by transforming the environment, contribute to changing the selective pressures which, in turn, prompt further adaptive responses from the organisms and, therefore, affect their fitness.

With regard to speciation, we can understand the importance of niche construction by appreciating its role in contributing to two mechanisms that favor optimal adaptation: the stabilization of environmental factors and the isolation

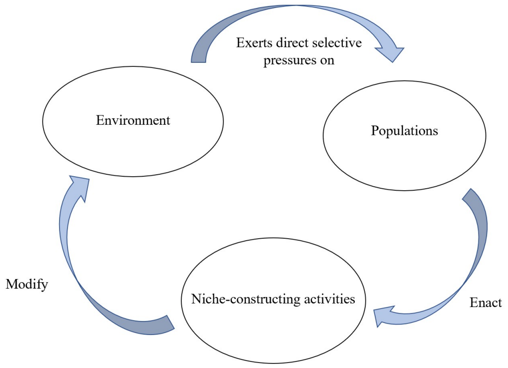

Figure 1: The interrelationships between organisms and environment, as conceptualized by niche-construction theory.

of the population from new variants. First, we must consider that optimal adaptation of a population to a certain environment is favored by the stabilization of the selective pressures. In other words, stable environmental pressures enable natural selection to operate towards the optimization of adaptive traits in a certain direction. On the other hand, unstable environmental conditions disrupt this trend, because they perturb the tendency of a population to specialize, that is, to develop traits optimally adapted to certain conditions, a tendency which increases their reproductive success (i.e., their fitness). However, for niche-constructing organisms the stabilization of selective pressures does not depend just on changes of the environment considered as an external independent variable. In fact, these organisms can contribute to stabilizing their selective environments by recreating favorable environmental factors through their modifications of the environment (cf. (Ackerly, 2003)). In addition to environmental stability, optimal adaptation can be hindered by the appearance of sub-optimal variants. While the availability of variants is necessary for natural selection to operate, too much variability – and the presence of extreme variants in particular – is an obstacle to optimal adaptation. Again, isolation is key to the effectiveness of selection, since a population of relatively limited size and geographically isolated is most favorable to fast evolution of traits adapted to specific environmental influences, as Darwin showed with the famous example of the Galapagos finches. Niche-constructing behaviors can contribute to isolating a population by preventing the introduction of new, potentially less adaptive, variants in the reproductive pool through mechanisms such as mating preferences (cf. (Rice, 1987)). In fact, the preference of certain organisms to reproduce with partners with certain phenotypic traits drives the selective pressures in a direction that favors that trait towards optimal adaptation. Through these two mechanisms, environment stabilization and isolation from the introduction of new variants through the restriction of the reproductive pool, niche construction works as an active process which recreates the environmental factors that positively impact a species reproductive success. In this sense, niche construction is a process that can enhance the isolation of a population by fostering independence from external selective pressures as well as from new variants emerging from the very population. In turn, isolation promotes the directionality of selection, that is the tendency towards specialization and optimal adaptation.

The second aspect related to biological speciation that we want to examine is the mechanism of genetic divergence. Genetic divergence is the process by which two or more populations with common origin accumulate independent genetic changes through time. This process may lead to reproductive isolation and, thus, can be at the root of speciation events. More specifically, the mechanism behind an event of speciation by genetic divergence is the following. After a certain period during which individual variants of a biological population have pursued unexploited resources, such as, for instance, certain food resources that are not exploitable by the original population, the gene flow between the original population and the variant subgroup may start to decrease. This is because isolation mechanisms can start to lead members of the variant subgroup to reproduce more with other members of this subgroup, rather than with members of the original population (following the example above, because individuals that exploit the same food resources have more opportunity for interaction). Therefore, selection starts operating in two diverging directions for the original population and the variant subgroup, leading to genetic divergence. The cumulative effects of selection over the generations can have as a possible result that morphological differences between the two (sub)populations may arise. In some cases, morphological divergence leads to the impossibility of cross-breeding between the variant subgroup and the population of origin but, even if that is not the case, reproduction between these newly branched species is strongly discouraged by other selection mechanisms. We can see a graphical depiction of this step-wise process of genetic divergence in Figure 2.

Evolutionary theorists have recently stressed the significance of genetic divergence as a driver for speciation, because of its relative independence from the existence of physical barriers (cf. (Palumbi, 1994)). In fact, while in the Modern Synthesis speciation is driven by the central mechanism of geographic isolation of subgroups and the consequent cessation of the gene flow between the isolated subgroup and the original population, according to the Extended Evolutionary Synthesis (Laland et al., 2014, 2015) speciation does not require physical barriers or complete genetic block. Therefore, according to the most recent picture of evolution by natural selection, the emergence of a new variant that can exploit hitherto unexploited resources and the presence of sufficiently strong replication and isolation mechanisms are enough for natural selection to steer into diverging directions, each direction operating on a different subgroup of the population (cf. (Feder, Egan, and Nosil, 2012)). The cumulative effect of selection into diverging directions can lead to the emergence of different species, as depicted by Figure 3.

As we have seen, mating preferences represent a core mechanism involved in genetic divergence, in that they promote the reproductive isolation of a subgroup, thus enhancing the optimization of the adaptive trait(s) that make the

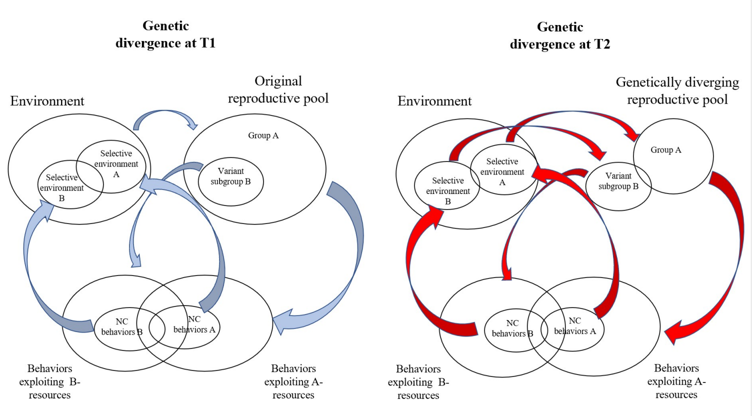

Figure 2: A graphic representation of two subsequent steps of the process of genetic divergence. At time T1 a variant subgroup within a population starts exploiting previously unexploited resources through certain behaviors (including some niche-constructing behaviors). Progressively this cycle might lead to diverging modifications of the selective environment, thus promoting the isolation of the subgroup and thus leading to genetic divergence (T2).

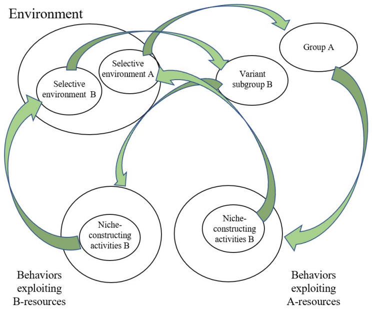

Figure 3: A graphic representation of a speciation episode resulting from the process of genetic divergence.

variant subgroup particularly fit to certain environmental conditions. This mechanism favors the optimal adaptation of the subgroup by restricting the reproductive pool from new variants that may lead the selection towards non-optimal adaptation. Even though mating preferences can indeed emerge as the result of selective pressures, they nevertheless influence the strength and direction of those very pressures, according to the dynamics that we have seen at work in niche construction. More precisely, mating preferences are a mechanism that, like other niche-constructing behaviors, contributes to recreate the environmental conditions that favorably impact a population reproductive success, in this case, isolation. In this sense, genetic divergence is influenced by the organisms' own preferences and activities, even though only indirectly, since these preferences and activities have an impact on some of the environmental factors which determine the very selective pressures acting on the organisms.

In sum, the cumulative adaptive gain that the variant subgroup obtains via isolation and genetic divergence is the result of the joint effect of direct selective pressures – which, at some point, start operating in diverging directions – and of organisms' preferences and activities. More specifically, mating preferences indirectly affect the direction of selection by modifying certain environmental conditions, thus enhancing isolation, which can lead to genetic divergence and, ultimately, to speciation events. In this way, similarly to what we highlighted in the case of niche-construction, we can see how a feedback-loop dynamic is at the heart of the process of genetic divergence, a widespread dynamic in biological systems (cf. (Lehtonen and Kokko, 2012)). In the next section, we will identify how a feedback loop analogous to the one of genetic divergence is at play in the context of scientific development and how it can adequately capture the dynamics of scientific branching, including methodology-centered scientific specializations.

5 Scientific Specialization by Value Divergence

We saw in the last section that the Extended Evolutionary Synthesis identifies specific mechanisms that make sense of how biological populations can undergo speciation also in the absence of physical barriers. Specifically, we saw that biological populations, via their niche-constructing activities, are able to actively contribute to a process of positive feedback loop between environmental pressures and mating preferences that may push natural selection to operate into diverging directions between different subpopulations, a process that may ultimately lead to a speciation event. In this section, we will see that this process of speciation driven by genetic divergence gives us a blueprint for understanding the possibility of methodology-centered episodes of scientific specialization as driven by a process of value divergence. Such a blueprint will offer us a way of expanding Kuhn's analogy between biological speciation and scientific specialization to cases of specialization where lexical diversity is not the most important driving factor (cf. Section 3).

In order to draw the analogy between speciation by genetic divergence and scientific specialization driven by value differences, we need first to see whether in scientific practice we can find analogues of the two main components that we saw at work in biological speciation in the absence of physical barriers: niche-constructing activities and genetic divergence.

The idea that scientific practice has elements that are strongly analogous to niche-constructing activities in evolutionary theory is explicitly discussed by Kuhn in "The Road since Structure" (Kuhn, 1990). Inspired by his reading of Lewontin's work on adaptation and biological niches (Lewontin, 1978), Kuhn (Kuhn, 1990) suggests that the relationship between scientists and the external world is structurally analogous to the way in which organisms and the environment influence one another in niche construction. According to niche-construction theorists, as we briefly saw in Section 4, both the primary, direct selective pressure exerted by the environment on organisms and the secondary, indirect selective influence exerted by organisms themselves by transforming the environment through their activities, contribute to the building of niches over time. Therefore, niches result from a process of co-construction involving both the organisms and the environment. According to Kuhn, an analogous co-construction underlies the emergence of phenomenal worlds, i.e., the worlds in which scientists, working within a specific disciplinary matrix, live and operate.[4] These phenomenal worlds, or, in our terminology, worldviews, are co-constructed by the scientists and the external world. More specifically, Kuhn stresses that, by adopting a disciplinary matrix, scientists commit to a set of research questions, methods, taxonomic and ontological assumptions, etc., which, in turn, partially determine a scientific community's worldview, that is, the phenomenal world in which the community live and operate. According to Kuhn, then, the worldview of a scientific community shapes the way in which the scientists working within it engage with their research questions and organize their cognitive practices, thus reverberating in the social and cultural structure of scientific inquiry. Therefore, if taken seriously from an evolutionary standpoint, the analogy between scientific communities and niche-constructing populations emphasizes the active role of scientists' preferences in modifying the external environmental pressures operating in the process of scientific development.[5] To further clarify this analogy, and to draw our more general analogy between biological speciation by genetic divergence and scientific specialization by value divergence, we need to see what can play the analogue of genetic divergence in the scientific realm.

If a scientific analogue to niche-construction activities is explicitly provided by Kuhn, in order to understand what might play the role of genetic divergence in methodology-centered episodes of scientific specialization we need to do more work. A good place to start is the notion of feedback loop, a notion that plays a central role in recent explanations of the process behind biological speciation by genetic divergence (cf. Lehtonen and Kokko 2012). A feedback loop is a phenomenon in virtue of which the outputs of a certain system at time t_1 become inputs for the same system at time t_2. In other words, a feedback loop occurs when the outcome of a process feeds back into the system. This is the mechanism that, as an example, niche-construction theorists use to con-

---

[4] It should be noted that the precise meaning and ontological status of 'world' in Kuhn and in particular in Kuhn's niche-construction analogy is a subject of controversy in Kuhn scholarship. For different takes on the matter, see, for instance, (Hoyningen-Huene, 1993; Bird, 2000; De Benedetto and Luchetti, Forthcoming).

[5] This active role of scientists' epistemic activities in modifying the external environmental pressures of scientific development is also stressed by Haufe (Haufe, 2022), in his evolutionary account of scientific development. Despite a similar reliance on an analogy with niche construction and genetic divergence theories, our account radically diverges from his in that our focus is mainly on the role of epistemic values and on the related, crucial feedback-loop mechanism behind scientists' niche-constructing activities.

ceptualize the complex relationship between organisms and their environments. According to niche-construction theory, as we have seen, while the environment operates a direct selection on organisms, organisms indirectly contribute to modifying environmental selective pressures by enacting niche-constructing behaviors that transform the environment. In this way, then, the output of the selective pressures that the environment exerts on organisms feeds back into the environment through the mediating role of the organisms' niche-constructing behaviors. Kuhn explicitly used the idea of feedback loop in the context of his discussion of the role of epistemic values in scientific theory choice in "Objectivity, Value Judgment, and Theory Choice" (Kuhn, 1977). Even though Kuhn holds the core set of epistemic values to be relatively fixed across time (cf. also Kuhn 1983b), in some passages he suggests that, in the process of theory change, values are affected too. In fact, according to Kuhn, epistemic values should be considered, to a certain extent, as historically changing entities, since "both the application of these values and, more obviously, the relative weights attached to them have varied markedly with time and also with the field of application" (Kuhn, 1977, p. 335). More precisely, we can identify a pattern of covariance between values and theories, whereby changes in the application or weight of values often follow changes in scientific theories. Kuhn qualifies this covariance as "a feedback loop through which theory change affects the values which led to that change" (Kuhn, 1977, p. 336). While Kuhn does not further elaborate on this point, De Benedetto and Luchetti (Forthcoming, MS) have provided a detailed analysis of the feedback-loop idea in Kuhn's thought and identified its foundational role for a dynamic picture of theory choice. Of particular interest for the purposes of this paper is their focus on how the idea of feedback loop is the core mechanism underlying the emergence of a certain worldview from the adoption of a disciplinary matrix (cf. De Benedetto and Luchetti Forthcoming). More specifically, they identify the following mechanism. First, scientific communities adopt the disciplinary matrices within which they operate, that is, they directly select them. In turn, these disciplinary matrices, as Kuhn (Kuhn, 1970, 1974) has clearly stated several times, shape the worldviews held by scientists. This is because adopting a disciplinary matrix requires accepting a lexicon and a set of values that fundamentally structure the phenomenal experience, beliefs and practices of a scientific community. In this way, the idea of feedback loop as the mechanism behind the emergence of a certain scientific community's worldview directly connects with Kuhn's aforementioned niche-construction analogy: while scientific communities directly select disciplinary matrices, these matrices indirectly influence scientific communities by shaping and transforming features of their worldview. It is through this specific feedback-loop dynamic that worldviews, just like biological niches, are co-constructed by scientific communities and disciplinary matrices.[6]

We can now better qualify how methodology-centered scientific specializa-

---

[6] Note that this analogy between niche-construction and a scientific community's worldview construction is different from (yet compatible with) Kuhn's original niche-construction analogy, with which we opened this section. For details about the interrelationship between these two analogies, see (De Benedetto and Luchetti, Forthcoming).

tion can be understood as a result of a mechanism analogous to the one that produces episodes of biological speciation driven by genetic divergence. The key mechanism to understand this analogy is the niche-constructing activity of scientific communities reinforced by the positive feedback-loop effect between a scientific community, its worldview, and its disciplinary matrix. In a way analogous to how niche-constructing biological populations recreate the environmental factors that influence their reproductive success, scientific communities stabilize the selective pressures to achieve optimal adaptation of their epistemic practices, that is, specialization. This stabilization is favored by mechanisms analogous to the biological domain, in that they promote the isolation of a population. Mating preferences are a core example, since they limit the emergence of new variants within a population and optimize the directionality of selective pressures towards certain adaptive traits. In the case of a scientific community, the relative isolation of a community contributes to the refinement, for instance, of certain lexical and taxonomic choices so as to improve their capacity to solve certain problems. In this respect, Kuhn rightly identified the isolation of a scientific community as the most important factor to promote its ability to specialize. Yet, as we stressed in Section 3, Kuhn's identification of taxonomic divergence as the only mechanism underlying isolation is too narrow, and his emphasis on geographic isolation, essential to the theory of speciation of the Modern Synthesis, has been challenged by supporters of the Extended Evolutionary Synthesis, as we saw in Section 4. First of all, the restriction of the reproductive pool as a mechanism promoting isolation does not only aim at preventing the introduction of lexical or taxonomic variants. The preferences of a scientific subgroup that restrict the emergence of variants can indeed refer to a variety of items involved in the epistemic activities of a scientific community, including methodologies, material practices, and most importantly for us, values. In this sense, a scientific community has several ways to actively isolate itself from intellectual influences that may disrupt their directional development towards optimal adaptation and the advantage gained through the cumulative adaptations from previous generations. This cumulative gain is what results from the feedback-loop dynamic that we see at work in niche-constructing biological populations and, analogously, in scientific communities regarded as epistemic niches.

In this feedback-loop dynamic, epistemic values play a crucial role, a role analogous to niche-constructing behaviors in biological speciation, as the main drivers of methodology-centered branchings of scientific disciplines. Methodology branchings start with the emergence of some methodological variation within a scientific community. Such variation produces differences in the disciplinary matrix of a specific subgroup of the scientific community. This subgroup, operating within a different disciplinary matrix, might weigh and apply epistemic values in a different way than their original group, given the close association between epistemic values and scientific methodologies. These different weightings and application of epistemic values may, in turn, impact the worldview of the subgroup, which might start diverging from the original worldview of the scientific community. Since the worldview shapes the practice of a scientific community, a subgroup with a different worldview might modify certain methodological, ontological, and theoretical components of the subgroup's disciplinary matrix. Such a loop, depicted in Figure 4, increase overtime the methodological divergence between the subgroup and the original group, up to the point of a proper event of scientific specialization, as depicted in Figure 5. This is the answer to our question on the role of values in methodology-centered specialization (cf. Sec. 2): values are crucial drivers of the positive feedback-loop dynamic between a scientific community, its worldview, and its disciplinary matrix behind methodology-centered episodes of scientific specialization.

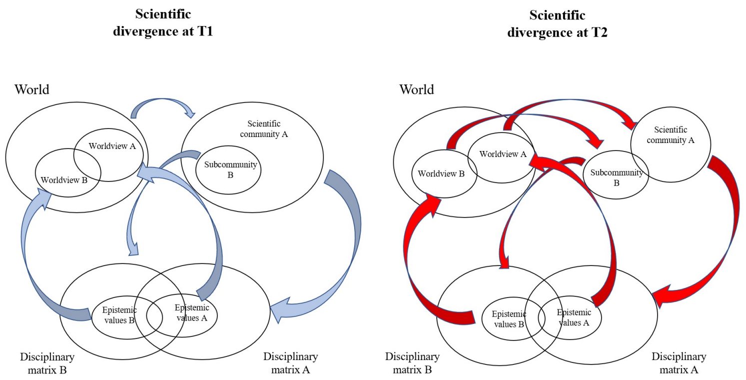

Figure 4: The progressive adoption of a different disciplinary matrix, including a set of epistemic values with different interpretation and or weightings than in the original matrix, by the emerging scientific subcommunity B leads to the modification of their scientific worldview and, in turn, to diverging selective pressures compared to those affecting the community of origin.

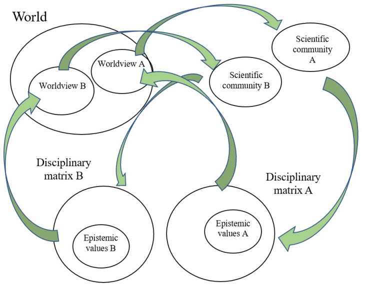

Figure 5: A graphic representation of a methodology-driven episode of scientific specialization resulting from the process of value divergence.

To emphasize the role of values in this feedback-loop process of scientific niche construction, we will briefly reconsider a case discussed as an episode of methodology-centered scientific specialization in Section 3, i.e., the emergence of molecular biology.

Molecular biology developed as an autonomous discipline in the 1930s and 40s to become institutionalized in the two subsequent decades. Historical accounts characterize the emergence of molecular biology – sometimes regarded as a full-blown scientific revolution – as rooted in the effort to answer questions on the nature of inheritance and the structure of the gene that classical genetics had left unanswered.[7] This effort required contributions from several disciplines, including chemistry, crystallography, information theory, and mathematics. As Politi (2018) highlights, rather than a mere migration of scientists from their original research fields, the emergence of molecular biology required the development of a new paradigm, or a new disciplinary matrix, to follow our choice of Kuhnian language. Scientists coming from different disciplines progressively developed novel experimental techniques, tools, and concepts in order to focus on a specific set of unanswered problems. Such a situation is analogous, in our extended Kuhnian speciation analogy, to the situation in which a variant subgroup of a biological population starts to exploit previously unexploited resources thanks to new phenotypic traits. Most importantly, the problems tackled by these scientists did not require major innovations with respect to the language used by classical geneticists, but instead radically novel methodological approaches, thus qualifying the emergence of molecular biology as a case of specialization centered around methodological incommensurability.

To better support the analogy with biological speciation, we must emphasize that a process of divergence from genetics of the soon-to-be molecular biology community occurred before the institutionalization of molecular biology as a discipline. Specifically, the key role in this pre-institutionalized divergence process is played by the novel experimental methods of molecular biology. These methods were, in fact, thought to be more effective than those of classical genetics to pursue questions on heredity that were still unanswered and, crucially for us, new questions concerning the molecular structure of the gene. These novel experimental methods were furthermore central to the slowly emerging new disciplinary matrix of molecular biology. Such a matrix included, among other components, certain epistemic values (as well as their application and weighting). A paradigmatic example of these values is what Kuhn (Kuhn, 1977) called breadth of scope, a value that arguably played a crucial role in the consolidation of molecular biology as an independent discipline. In order to see how the emphasis on the breadth of scope as an epistemic value is constitutive of the disciplinary matrix of molecular biology, it helps to look at the case of the Central Dogma of molecular biology. The Central Dogma states that genetic information flows only in one direction, from DNA, to RNA, and then to proteins, or, from RNA directly to proteins. While the commitment to this piece of theory has proved to be an astonishingly effective driver for the growth of molecular biology, its empirical adequacy has been contested (cf. Koestler and Smythies

---

[7] For historical accounts of the emergence of molecular biology, see (Fischer and Lipson 1988, Olby 1990, 1994, Judson 1996, Rheinberger 1997, Morange 1998, de Chadarevian 2002, Witkowski 2005, van Holde and Zlatanova 2018).

1969; Keyes 1999; Stotz 2006; Griffiths and Stotz 2013; Camacho 2019). In this way, the commitment to the Central Dogma warranted a broad explanatory scope to the framework of molecular biology, in spite of sacrificing some empirical adequacy. The importance of the broad explanatory role attributed to linear causal mechanisms, illustrated by the Central Dogma, became a hallmark that distinguished molecular biology and further contributed to carving its distinctive identity within the life sciences in the 1950s and 60s (Keller 1990). In this way, we can see an instantiation of our value-driven feedback-loop mechanism between a scientific community, its worldview, and its disciplinary matrix. First, a scientific subcommunity starts using a different methodology (i.e., the novel experimental methods of molecular biology). Then, these different methods determined a different weighting of epistemic values (i.e., the increasing focus on breadth of scope of molecular biologists). These different weighting of epistemic values shaped, in turn, the different worldview of the emerging subcommunity (i.e., the community of molecular biologists). Over time, this feedback-loop dynamic produces a progressive isolation of the "variant" scientific subgroup from the scientific community of origin. This is because the progressive isolation of the diverging subcommunity leads it to further reduce exchanges with the original community, thus corroborating the methodological difference between the two communities. This feedback-loop mechanism can eventually lead to a branching episode in science, such as the present case of the emergence of molecular biology, mostly driven by methodological differences.

6 Conclusion

Let us recap the main steps of this work. We started by analyzing Kuhn's original formulation of the so-called speciation analogy, i.e., the analogy between biological speciation and scientific specialization, stressing Kuhn's heavily language-centered understanding of this analogy. Then, we discussed the limits of such a language-centered understanding of scientific specialization (and, consequently, of the speciation analogy), by recalling how philosophy and history of science discuss episodes of scientific specialization that are not centered around lexical differences, but rather around methodological differences. Thus, we set ourselves the task of extending Kuhn's speciation analogy to model also these methodology-centered episodes of specialization. In order to do that, we drew inspiration from recent findings of evolutionary biology on the phenomenon of speciation by genetic divergence, i.e., a subclass of speciation events where biological populations undergo speciation in the absence of physical barriers. In analogy with speciation by genetic divergence, we proposed to understand methodology-centered episodes of scientific specialization as cases of specialization by value divergence. We then showed an application of our proposed model of specialization by value divergence by reconstructing the emergence of molecular biology as driven by value divergence.

Taking stock, we can see now how, in the light of recent evolutonary biology, Kuhn's speciation analogy can be extended beyond Kuhn's linguistic focus to account for the diverse mechanisms at work in different episodes of scientific specialization. Moreover, our model of scientific specialization by value divergence demonstrates once again the ubiquity of epistemic values in science and the significance of the feedback-loop mechanisms involving them.

References

Ackerly, D.D. (2003). "Community assembly, niche conservatism, and adaptive evolution in changing environments". *International Journal of Plant Sciences 164*(S3), S165-S184.

Bird, A. (2000). *Thomas Kuhn.* Routledge, London.

Bird, A. (2002). "Kuhn's wrong turning". *Studies in History and Philosophy of Science 33*, 443-463.

Camacho, M.P. (2019). "The central dogma is empirically inadequate... no matter how we slice it". *Philosophy, Theory, and Practice in Biology 11*(6).

Campbell, D.T. (1974). "Evolutionary Epistemology". In Schilpp, P. (Ed.), *The Philosophy of Karl R. Popper*, Open Court, LaSalle, 412-463.

Carrier, M. (2013). "Values and objectivity in science: Value-ladenness, pluralism and the epistemic attitude". *Science & Education 22*, 2547-2568.

de Chadarevian (2002). *Designs for Life: Molecular Biology after World War II.* Cambridge University Press, New York.

Chang, H. (2012). *Is Water H2O? Evidence, Realism and Pluralism.* Boston Studies in the Philosophy and History of Science, Springer, Cham.

Chang, H. (2013). "Incommensurability: Revisiting the chemical revolution". In Arabatzis, T. and Kindi, V. (Eds.), *Kuhn's the structure of scientific revolutions revisited*, Routledge, Abingdon, 153-178.

Darwin, C. (1859): *The Origin of Species.* John Murray, London.

De Benedetto and Luchetti (Forthcoming). "Worlds, Algorithms, and Niches: the feedback-loop idea in Kuhn's philosophy". Forthcoming in Shan, Y. (Ed.), *Rethinking Thomas Kuhn's Legacy*, Boston Studies in the Philosophy and History of Science, Springer, Cham.

De Benedetto and Luchetti (MS). "Theory Choice as Niche Construction: The feedback loop between scientific theories and epistemic values". *Manuscript.*

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

Feder, J.L., Egan, S.P., and Nosil, P. (2012). "The genomics of speciation-with-gene-flow". *Trends in genetics, 28*(7), 342-350.

Feest, U. (2014). “Phenomenal experiences, first-person methods, and the artificiality of experimental data”. *Philosophy of Science 81*(5), 927-939.

Fischer, E.P. and Lipson, C. (1988). *Thinking about Science: Max Delbrueck and the Origins of Molecular Biology.* W.W. Norton, New York.

Friedman, M. (2001). *Dynamics of Reason: The 1999 Kant Lectures at Standford University.* CSLI Publications, Standford (CA).

Griffiths, P. and Stotz, K. (2013). *Genetics and Philosophy: An introduction.* Cambridge University Press, Cambridge.

Haufe, C. (2022). *How Knowledge Grows: The Evolutionary Development of Scientific Practice.* MIT Press, Cambridge (MA).

van Holde, K.E. and Zlatanova, J. (2018). *The Evolution of Molecular Biology: The Search for the Secrets of Life.* Academic Press, London.

Hoyningen-Huene, P. (1993). *Reconstructing Scientific Revolutions: Thomas S. Kuhn’s Philosophy of Science.* University of Chicago Press, Chicago.

Hoyningen-Huene, P. and Sankey, H. (2001). *Incommensurability and related matters.* Springer, Dordrecht.

Hull, D.L. (2001). *Science as a Process: an Evolutionary Account of the Social and Conceptual Development of Science.* University of Chicago Press, Chicago.

Judson, H.F. (1996). *The Eight Day of Creation: The Makers of the Revolution in Biology, Expanded Edition.* Cold Spring Harbor Laboratory Press, Cold Spring Harbor (NY).

Keyes, M.E. (1999): “The Prion Challenge to the Central Dogma of Molecular Biology, 1965-1991: Part II: The Problem with Prions”. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences 30*(2), 181-218.

Kitcher, P. (1978): “Theories, Theorists, and Theoretical Change”. *The Philosophical Review 87*(4), 519-547.

Koestler, A., and Smythies, J.R. (1969). *Beyond Reductionism: New Perspectives in the Life Sciences.* The MacMillan Co., New York.

Kuhn, T.S. (1962). *The Structure of Scientific revolution.* International Encyclopedia of Unified Science, vol. 2, no. 2., University of Chicago Press, Chicago.

Kuhn, T.S. (1970). *The Structure of Scientific revolution.* Second Edition, University of Chicago Press, Chicago.

Kuhn, T.S. (1974). “Second Thoughts on Paradigms”. In Suppe, F. (Ed.), *The Structure of Scientific Theories*, University of Illinois Press, Chicago, 459-482.

Kuhn, T.S. (1977). “Objectivity, Value Judgment, and Theory Choice”. In Thomas Kuhn, *The Essential Tension: Selected Studies in Scientific Tradition and Change*, Chicago University Press, Chicago, 320-339.

Kuhn, T.S. (1983a). “Commensurability, Comparability, Communicability”. In *PSA: Proceedings of the biennial meeting of the philosophy of science association*, 669-688.

Kuhn, T.S. (1983b). “Rationality and Theory Choice”. *Journal of Philosophy 80*, 563-570.

Kuhn, T.S. (1989). “Possible Worlds in History of Science”. In Sture, A. (Ed.), *Possible Worlds in Humanities, Arts, and Sciences*, De Gruyter, Berlin & New York, 9-32.

Kuhn, T.S. (1990). “The Road Since Structure”. In *PSA: Proceedings of the biennial meeting of the philosophy of science association* (2), 3-13.

Kuhn, T.S. (1993). “Afterwords”. In *The Road Since Structure*, 2000, 224-252.

Kuukkanen, J. (2012). “The Concept of Evolution in Kuhn’s Philosophy”. In Kindi, V. and Arabatzis, T. (Eds.), *Kuhn’s The Structure of Scientific Revolutions Revisited*, Routledge, New York, 134-153.

Kuukkanen, J. (2021). “Truth, Incoherence, and the Evolution of Science”. In Wray, K.B. (Ed.), *Interpreting Kuhn: Critical Essays*, Cambridge University Press, Cambridge, 202-221.

Lacey, H. (1999). *Is Science Value Free?: Values and Scientific Understanding.* Routledge, London.

Lakatos, I. (1978). “Falsification and the Methodology of Scientific Research Programmes”. In Worrall, J. and Currie, G. (Eds.), *The Methodology of Scientific Research Programmes*, Cambridge University Press, Cambridge, 8-101.

Lakatos, I. and Musgrave, A. (Eds.) (1970): *Criticism and the Growth of Knowledge.* Cambridge University Press, Cambridge.

Laland, K., Uller, T., Feldman, M., Sterelny, K., Müller, G.B., Moczek, A., Jablonka, E., Wray, G.A., Hoekstra, H.E., Futuyma, D.J., Lenski, R.E., Mackay, T.F.C., Schluter, D., and Strassman, J.E. (2014): “Does evolutionary theory need a rethink?”. *Nature News 514* (7521), 161-164.

Laland, K.N., Uller, T., Feldman, M.W., Sterelny, K., Müller, G.B., Moczek, A., Jablonka, E. and Odling-Smee, J. (2015): “The extended evolutionary synthesis: its structure, assumptions and predictions ”. *Proceedings of the royal society B: biological sciences 282* (1813), 20151019.

Laudan, L. (1978). *Progress and its problems: Towards a theory of scientific growth.* University of California Press, Berkeley.

Laudan, L. (1981): "A Confutation of Convergent Realism". *Philosophy of Science 48*(1), 19-49.

Laudan, L. (1984). *Science and Values: The Aims of Science and their Role in Scientific Debate*. University of California Press, Berkeley.

Laudan, L. (2004). "The Epistemic, the Cognitive, and the Social". In Peter Machamer & Gereon Wolters (Eds.), *Science, values, and objectivity.* Pittsburgh, PA: University of Pittsburgh Press, 14-23.

Lehtonen, J. and Kokko, H. (2012)."Positive feedback and alternative stable states in inbreeding, cooperation, sex roles and other evolutionary processes". *Philosophical Transactions of the Royal Society B: Biological Sciences 367*(1586), 211-221.

Lewontin, R.C. (1978)."Adaptation". *Scientific American 239*(3), 212-230.

Longino, H.E. (1990). *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry.* Princeton University Press, Princeton (NJ).

Marcum, J. (2015). "The Evolving Notion and Role of Kuhn's Incommensurability Thesis". In Devlin, W.J. and Bokulich, A. (Eds.), *Kuhn's Structure of Scientific Revolutions - 50 years on*, Boston Studies in the Philosophy and History of Science (vol. 311), Springer, 115-134.

McMullin, E. (1983). "Values in Science". *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association 1982* (4), 3-28.

McMullin, E. (2014). "The Virtue of a Good Theory". In Curd, M. and Psillos, S. (Eds.), *The Routledge Companion to Philosophy of Science*, Second Edition, Routledge, London, 561–571.

Morange, M. (1998). *A History of Molecular Biology.* Harvard University Press, Cambridge (MA).

Nosil, P. (2012). *Ecological Speciation.* Oxford University Press, Oxford.

Oberheim, E. and Hoyningen-Huene, P. (2018). "The Incommensurability of Scientific Theories". *The Stanford Encyclopedia of Philosophy* (Fall 2018 Edition), Edward N. Zalta (ed.), URL = ¡https://plato.stanford.edu/archives/fall2018/entries/incommensurability/¿.

Odling-Smee, F.J., Laland, K.N. and Feldman, M.W. (2003). *Niche Construction: the Neglected Process in Evolution.* Princeton University Press, Princeton (NJ).

Okasha, S. (2011). "Theory Choice and Social Choice: Kuhn versus Arrow". *Mind 120* (477), 83-115.

Olby, R. (1990). “The Molecular Revolution in Biology”. In R.C. Olby et. al. (Eds.), *Companion to the History of Modern Science*, Routledge, New York, 503-520.

Olby, R. (1994). *The Path to the Double Helix: The Discovery of DNA*. Revised Edition, Dover, New York.

Palumbi, S.R. (1994). “Genetic Divergence, Reproductive Isolation, and Marine Speciation”. *Annual Review of Ecology and Systematics 25*, 547-572.

Politi, V. (2018). “Scientific revolutions, specialization and the discovery of the structure of DNA: toward a new picture of the development of the sciences”. *Synthese 195*(5) 2267-2293.

Politi, V. (2019). “Specialisation and the Incommensurability Among Scientific Specialties”. *Journal for General Philosophy of Science 50*, 129-144.

Popper, K.R. (1972). *Objective Knowledge: An Evolutionary Approach.* Clarendon Press, Oxford.

Psillos, S. (1999): *Scientific Realism: How Science Tracks Truth.* Routledge, London.

Renzi, B.G. (2009). “Kuhn’s Evolutionary Epistemology and Its Being Undermined by Inadequate Biological Concepts”. *Philosophy of Science 76*, 143-159.

Reydon, T.A.C. and Hoyningen-Huene, P. (2010). “Discussion: Kuhn’s Evolutionary Analogy in *The Structure of Scientific Revolutions* and “The Road since Structure”. *Philosophy of Science 77*, 468-476.

Rheinberger, H.J. (1997). *Towards a History of Epistemic Things: Synthesizing Proteins in the Test Tube.* Standford University Press, Standford (CA).

Rice, W.R. (1987). “Speciation via habitat specialization: the evolution of reproductive isolation as a correlated character”. *Evolutionary Ecology 1*, 301-314.

Sankey, H. (1993). “Kuhn’s Changing Concept of Incommensurability”. *British Journal for the Philosophy of Science 44*, 759-774.

Sankey, H. (1994). *The Incommensurability Thesis.* Abingdon: Taylor and Francis.

Sankey, H. (1995). “The problem of rational theory-choice”. *Epistemologia 18* (2):299-312.

Sankey, H. (1997). “Taxonomic Incommensurability”. In Sankey, H. (Ed.), *Rationality, Relativism, and Incommensurability*, Ashgate, London, 66-80.

Shan, Y. (2020a). “Kuhn’s ‘Wrong Turning’ and Legacy Today”. *Synthese 197*(1), 381-406.

Shan, Y. (2020b). *Doing Integrated History and Philosophy of Science: A Case Study of the Origin of Genetics*. Boston Studies in the Philosophy and the History of Science, Springer, Cham.

Shapere, D. (1966). "Meaning and scientific change". In Colodny, R. (Ed.), *Mind and cosmos: Essays in contemporary science and philosophy*, University of Pittsburgh Press, Pittsburgh, 41-85.

Solomon, M. (2001). *Social Empiricism*. MIT Press, Cambridge (MA).

Stegmüller, W. (1976): *The Structure and Dynamics of Theories*. Springer-Verlag, Heidelberg.

Stotz, K. (2006). "Molecular Epigenesis: Distributed specificity as a break in the central dogma". *History and philosophy of the life sciences 28*(4), 533-548.

Witkowski, J. (Ed.) (2005).*The Inside Story: DNA to RNA to Protein*. Cold Spring Harbor Laboratory Press, New York.

Wray, K. B. (2011). *Kuhn's Evolutionary Social Epistemology*. Cambridge University Press, Cambridge.