This paper, **The Kuhnian Paradigm**, is a programmatic paper describing Kuhn's philosophy of science as a genuinely new paradigm for philosophy of science. As such it provides the frame for much of the rest of my work in philosophy of science, most importantly:

1) **An agent-based model of Kuhn's Structure of Scientific Revolutions**, where I show how possibly the interactions of individually rational scientists can result in an aggregate patter of normal science, crisis and revolution. Published in the Boston Studies in the Philosophy and History of Science (eds. Alisa Bokulic and William Devlin)
http://www.springer.com/philosophy/epistemology+and+philosophy+of+science/book/978-3-319-13382-9

The penultimate version of this paper can be downloaded for free at:
https://www.academia.edu/5964795/From_Theory_Choice_to_Theory_Search

2) **A Unified Model of the Division of Cognitive Labor**, a unification of Kitcher and Kuhn's ideas on the division of cognitive labor. This paper won the Philosophy of Science Graduate Student Essay award of the Philosophy of Science Association. Published in the journal Philosophy of Science.
http://www.jstor.org/discover/10.1086/676670?uid=3737592&uid=2134&uid=2&uid=70&uid=4&sid=21104891646057

The penultimate version of this paper can be downloaded for free at:
https://www.academia.edu/6405187/A_Unified_Model_of_the_Division_of_Cognitive_Labor

3) **A Comparison of Two Models of Scientific Progress**, where I build an agent-based model to make explicit Kuhn's (intriguing but rather vague and implicit) model of scientific progress and contrast its implications with the traditional linear model of progress. Published in Studies in History and Philosophy of Science. http://www.sciencedirect.com/science/article/pii/S0039368114000211

The penultimate version of this paper can be downloaded for free at:
https://www.academia.edu/4917138/A_Comparison_of_Two_Models_of_Scientific_Change

I strongly believe novel developments such as agent-based modeling and scientometric data make it possible to "upgrade" Kuhn's vision. The goal of this upgrade is to close the gap between the appeal of Kuhn's ideas for practicing scientists and the difficulties philosophers faced when trying to analyze them. The result is a new kind of philosophy of science that finds a better balance between philosophical rigor and societal relevance.

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The Kuhnian Paradigm

Rogier De Langhe

Perhaps the current situation in philosophy of science is similar to that of Ancient astronomy. In Ancient astronomy, the Aristotelian view based on static, perfect circles explained the movement of heavenly bodies but was not empirically adequate. The Ptolemaean view, on the other hand, allowed good predictions but did not explain them. Similarly sociological accounts of science are more empirically adequate but usually fail to explain why science works, while philosophical explanations of the workings of science tend to depart significantly from actual scientific practice. In an attempt at his own Copernican revolution, Thomas Kuhn tried to do both: adequately capture the challenges faced by practicing scientists without losing normative force. This resulted in an immensely popular book, the *Structure of Scientific Revolutions* (SSR 1962). The vision of an explanatory and empirically adequate general philosophy of science showed the potential to broaden the scope of philosophy of science to questions such as why disciplines tend to cluster in schools, why communities are reluctant to embrace novel frameworks and what drives scientific innovation. These questions are highly relevant for practicing scientists but have traditionally received little attention in philosophy of science. SSR's success makes it all the more frustrating that 50 years on few philosophers of science would call themselves "Kuhnians". Kuhn's view was never used as a starting point for broad-scale philosophical research but has itself remained the subject of scholarly debate. Whereas SSR thanks its immense popularity to the questions it raised, the paradigm was never sufficiently articulated to provide (apparently much-anticipated) answers. I claim this gap can now be closed. In this paper I explain why the gap was there in the first place, why it can now be bridged and what lies on the other end. In the first section I argue that the Kuhnian paradigm was not sufficiently articulated because Kuhn was one of the first to describe an instance of the interdisciplinary family of models that came to be known as "complex systems". In the second section I argue that recent developments provide powerful new tools for better articulating the Kuhnian paradigm. Kuhn is often credited for undermining the logical empiricist research consensus in philosophy of science in his time, but because of a lack of articulation the Kuhnian paradigm failed to provide an alternative research agenda, leaving the field in a state of fragmentation. 50 years on, these new tools might turn it into the genuine paradigm that Kuhn intended it to be, including both a descriptive and a normative research agenda. This program for a *systemic philosophy of science* is laid out in the third section.

1 Science as a Complex System

Already in SSR's opening pages Kuhn makes clear his revolutionary aspirations. Standard philosophy of science at the time restricted itself to the context of justification, as a result of which "it will, therefore, never be a permissible objection to an epistemological construction that actual thinking does not conform to it" (Reichenbach 1938, 6). Against this, Kuhn envisions a more empirical "new image of science" (SSR, 3) that was not confined to the finished products of science as represented in scientific textbooks, but based on the historiography of science. However Kuhn's recourse to case-studies led to disappointment, most explicitly in his essay *The Trouble with the Historical Philosophy of Science* in which he calls them "misleading" (Kuhn 2000, 111) because

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their study only deepens the problems they suggest rather than solving them. Instead, he came to realize that "many of the most central conclusions we drew from the historical record can be derived instead from first principles" (ibid. 112), and these principles "are necessary characteristics of any developmental or evolutionary process" (ibid. 119).[1] Here I argue that Kuhn probably realized that his account of science was an instance of a family of models that came to be called *complex systems*. This would explain Kuhn's two claims above; a complex system is an *evolving* system that can generate complex structure from *simple* rules. And the fact that research on complex systems was still in its infancy during most of Kuhn's lifetime would explain why Kuhn failed to articulate his account to the extent that it could be operationalized.

A complex system consists of many components, none of which needs to interact with all others. What makes it "complex" instead of merely "complicated" is that the rules governing these localized interactions change through time. For example a car is complicated. It consists of many locally interacting components, but the interaction between those components is stable and can be centrally controlled by the driver. Studying their parts is sufficient to understand how the car works. Traffic, on the other hand, is complex. Drivers adjust their behavior as a result of previous interactions (endogenous change), as a result of events outside the system (exogenous change) and usually both (the endogenous reinforcement of exogenous chance events). No single driver controls the system, yet these complex interactions can give rise to simple, stable patterns such as traffic jams. The system is thus capable of *self-organization*, a process that can occur at various levels and thus create a *hierarchy* within the system (e.g. food chains). Such patterns are called "emergent" because they cannot be understood as the sum of their parts. Rather they must be explained by reference to the *interaction* of their parts through *time*.

Kuhn's account of science can be interpreted as an attempt at describing science as a complex system. Kuhn describes how science emerges from the localized *interactions* of scientists through *time*. Exogenous chance events such as new instruments, new data and personal idiosyncracies cause change, and this change can in turn lead to further (endogenous) changes through "*a feedback loop through which theory change affects the values which led to that change*" (Kuhn 1977, 336). Such a feedback loop allows for the endogenous reinforcement of chance events, making possible critical events such as "scientific revolutions" and self-organization such as the emergence of relatively homogenous networks of scientists who share conceptual, theoretical, instrumental and methodological commitments, viz. "paradigms" (SSR, 42). Because of self-reinforcement "Small changes, however, can have large-scale effects" (Kuhn and Thomas 1990, 12), as a result of which very different paths can emerge under similar initial conditions, allowing incommensurability: "even men who, being in the same or in closely related fields, begin by studying many of the same books and achievements may acquire rather different paradigms in the course of professional specialization" (SSR, 49). The interaction between these emergent groupings results in aggregate patterns that, unlike the interactions of their components, might be simple and stable. In Kuhn's case: a cycle of normal science, crisis and revolution.

Although the development of the idea of Kuhn's account of science as a complex system is material for a paper in its own right, this brief sketch already indicates its potential to unify many different elements of his account. In addition I list here two other indications that suggest this interpretation is correct. First, the seemingly disparate analogies that Kuhn used throughout his work, such as institutional dynamics, political revolutions, biological evolution, ecosystem dynamics and cognitive dynamics, have turned out to be prime examples of what we now call "complex systems" (Newman 2011). For lack of a theoretical account to describe science as a complex system, Kuhn seems to have taken recourse to analogical descriptions using well-known properties of other such systems. Second, Kuhn was a Harvard condensed matter physicist (PhD 1949). Condensed matter systems such as magnets, crystals, glasses and superconductors are among the earliest known examples of complex systems and these were exactly the kind of systems that Kuhn had been working on for almost a decade before turning philosopher.

2 New Tools for the Articulation of the Kuhnian Paradigm

I have been arguing that the lack of articulation of the Kuhnian paradigm prevented it from being operationalized and that this lack of articulation is not due to the questions it asked but to the answers it provided. Philosophers were not satisfied with the answers Kuhn provided on all levels: input, output and their connection.

1. The core concepts allow for too many alternative interpretations (Masterman and Margaret 1970),
2. no clear mechanism for rationality and progress is laid out (Sharrock and Read 2003),
3. empirical support is indirect and inconclusive: particular historical case studies to support claims about general patterns in science (Kuhn 2000, 109).

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[1] Kuhn had started developing this view in a book project that was never finished due to his untimely death in 1996 and for legal reasons the material is inaccessible to this day.

In the previous section I have argued that these shortcomings stem from the fact that Kuhn tried to describe science as a complex system while this field was still in its infancy at the time. In this section I will argue that this situation has now changed. Describing science as a complex adaptive system requires hypotheses about how possibly its emergent features can be produced from the localized interactions of its components, and the right data to test them. The onset of Big Data, the resulting surge in network theory, and the increased computational power to analyze that data and carry out simulations, are recent and substantial developments that were largely unavailable during Kuhn's lifetime. Developments outside philosophy have previously shown the ability to have an enormous impact on our philosophical understanding. The following breakthroughs related to complex systems could be for the Kuhnian paradigm what the breakthroughs in logic were for logic empiricism.

2.1 Network Theory

The exemplar of a complex adaptive system is a *network*, a structure composed of many interconnected components or nodes that interact locally through links with their neighbors. Through time these networks evolve by events such as the rewiring between nodes or the addition of new nodes and links. In recent years there has been renewed interest in the properties of evolving networks such as the *small-world property*. In most networks the longest path between two nodes increases proportional to the number of nodes in the network. But at least since Milgram's Small World experiment (Travers and Milgram 1969) scholars have been aware of the fact that in some networks the distance between any two nodes is surprisingly small. The small world property has the advantage of very efficient transmission of information on the network and high resilience against errors of the network (although more vulnerable to targeted attacks, see Albert et al. 2000). Although small world networks are only a small set of possible networks, the onset of Big Data has revealed that a surprisingly large amount of actual networks exhibit this property, e.g. the world wide web, neuronal networks, citation networks, telephone call networks, food chains, electric power grids and metabolite processing networks. By the late 1990's this prompted physicists to start developing general theories showing how possibly a network could have the small-world property (Watts and Strogatz 1998; Barabasi and Albert 1999). More generally, new and abundant network data has led to a surge in the theory of evolving networks in the last 15 years, drawing heavily on pre-existing tools from condensed matter physics (Albert and Barabasi 2002). It is increasingly clear that the topology and evolution of networks is governed by robust organizing principles (Newman 2011). They might provide exactly what Kuhn was looking for by the end of his life: first principles that are necessary characteristics of any developmental or evolutionary process.

Insights from network theory can help articulating the Kuhnian paradigm on all three levels. First, network theory provides a formal framework originating from graph theory in mathematics and condensed matter physics within which notions such as "paradigm", "exemplar" and "incommensurability" could acquire an interpretation of unprecedented detail. Secondly, it can suggest mechanisms for how possibly a network of conceptual, theoretical, instrumental and methodological commitments could self-organize through local interaction rules into paradigms that exhibit critical behavior. Thirdly it can help to operationalize Kuhnian phenomena, possibly leading to novel empirical predictions and a clearer view on exactly what data is relevant. For example the increasing ability to statistically identify phases and phase transitions on networks might operationalize the notions of normal vs. revolutionary science and pre-paradigmatic vs. paradigmatic science. The feasibility of this project is illustrated by the fact that these methods have already successfully been employed by Kiyono et al. (2006) to detect different phases in financial data. Similar research on bibliometric data might reveal the existence of normal and revolutionary phases in science. This would constitute a significant philosophical result achieved by empirical means. It also suggests a normative agenda for a systemic philosophy of science aimed at optimizing information flows *on* networks, increasing the resilience *of* networks and optimizing the interconnectivity *between* networks.

2.2 Agent-Based Modeling

One reason why the study of complex adaptive systems is relatively new is that the dynamics emerging from localized interaction are often beyond reach of pure mathematical methods (Bonabeau 2002). The alternative is to explore possibility space by simulating the possible interactions of the components or agents of a system in an *agent-based model*. An agent-based model is a computational model for simulating the interaction of autonomous agents to observe the behavior of the aggregate system. Simple agent-based models can produce surprisingly strong results. For example Thomas Schelling (1978) demonstrated with his exemplary checkerboard model that just a small racial preference is already sufficient to produce strictly segregated neighborhoods over time. Although Schelling made his model using only paper and pencil, canvassing possibility space often requires the computation of a vast number of possible scenarios and hence advanced agent-based models require computational power of a size that

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for long was not widely available. Moreover the development of such models typically required substantial programming skills. Only recently has low-barrier software such as Netlogo enabled a broader use of these models, accompanied by the emergence of methodological guidelines for their construction (Miller and Page 2007). Agent-based modeling can be used to articulate the Kuhnian paradigm by allowing to investigate how possibly local interaction rules can produce Kuhnian aggregate patterns such as "normal science", "revolution", "crisis", "paradigmatic" and "pre-paradigm" periods. If scientific activity behaves as a complex system, then science is a process. Agent-based simulations are uniquely suited for investigating not the outcomes but the process by which it was reached.

2.3 Big Data

The study of complex systems is characterized by the heavy use of statistics to study aggregate patterns emerging from complex underlying interactions. The scarcity of large and qualitative datasets has long been an impediment to its expansion beyond physics. Complex systems typically consist of a very large number of components, for example economic agents in a market, each with their own interactions through time. Only recently do we have the technical means to acquire, store and process such information. For example the famous small world result was obtained counting the steps it took letters to reach a given destination, and the final result was based on only 64 such letters. This situation has changed dramatically with the onset of "Big Data", vast datasets generated as a result of the digitization of our world. To give just one example, in 2008 Jure Leskovec replicated Milgram's result using the Microsoft Messenger instant-messaging network containing 255 billion messages sent by 240 million people. Scientometric data is part of this Big Data revolution, containing information about for example co-authorship, keywords and citations of scientific papers. It is a fresh and vast source of empirical data about the dynamics of science through time.

Just as Milgram, Kuhn made claims about system properties but had to content himself with anecdotal evidence, in his case from historical case-studies. Nevertheless he initially had huge expectations about the role the historiography of science could potentially play in his project of an empirically better informed philosophy of science. As noted above, this was a dead end. Kuhn seems to have realized this fairly quickly. Already in the postscript to SSR his hopes for identifying paradigms in empirical data shift to statistical data about science: "formal and informal communication networks including those discovered in correspondence and in the linkages among citations […]. Typically it may yield communities of perhaps one hundred members, occasionally significantly fewer. Communities of this sort are the units that this book has presented as the producers and validators of scientific knowledge. Paradigms are something shared by the members of such groups" (SSR, 178). Kuhn explicitly references Eugene Garfield, the founder of the Web of Science. Currently this is one of the largest scientometric databases in the world but back then the whole project was still in its infancy. Nevertheless Kuhn is convinced that this is the way to go: "*I take it that the job can and will be done*" (ibid.). Now more than 40 years after the postscript, this data exists and is readily available for analysis.

Perhaps surprisingly, the development of bibliometric databases has largely gone unnoticed for many philosophers of science. Philosophy of science has a long history of focusing on the products of science in relation to the world. But citations do not have, nor are they intended to have, any justificatory value; citing a paper does not mean one agrees with it. Yet citations anchor a paper in a network of similar papers. They are similar not in their opinion but in the more abstract sense of sharing what the question should be and what counts as a solution. Thus citations are, and are intended to be, anchoring a paper in a network of papers that address similar questions and uphold similar standards. So while citation data is meaningless from a justificatory point of view, for the Kuhnian paradigm it captures an elementary relation: citations indicate membership of the same paradigm, viz. sharing the same conceptual, theoretical, instrumental and methodological standard. A highly cited paper indicates that many other papers use it for anchoring. Such papers are exemplary. Citation networks are typically characterized by a power law distribution of citations. As a consequence there are "hubs" in the network, nodes with a disproportionately large amount of links. This operationalizes the notion of an *exemplar*. Such an exemplar exemplifies the problems and standards for the papers to which they are connected. This cluster in turn operationalizes the notion of a *paradigm* as a network of scientific practices connected by conceptual, theoretical, instrumental and methodological commitments (SSR, 42). Although the nodes connected to the hub tend not to be connected to other hubs, the hubs themselves are (see Fig. 1). This could explain Kuhn's claim that the most exemplary scientists typically contribute to multiple paradigms: "Usually individual scientists, particularly the ablest, will belong to several such groups either simultaneously or in succession" (SSR, 178). Shifts in growth rates of contributions to different paradigms can be used as an empirical proxy for a *revolution* described as "*an increasing shift in the distribution of professional allegiances*" (SSR, 15) This might lead to the production of conclusive statistical evidence about the existence of Kuhnian scientific revolutions.

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Fig. 1 An example of a network with 500 nodes with links distributed as a power law

The complex, evolving networks revealed in bibliometric data (co-author networks, citation networks, keyword networks,…) are the material reflection of science as a complex adaptive system. Because the Kuhnian paradigm can give meaning to a citation, it is able to incorporate this fresh and vast source of empirical data. It is one step closer to Kuhn's dream of a descriptively more adequate normative philosophy of science (Fig. 2).

3 Toward a Systemic Philosophy of Science

Kuhn is often credited with undermining the logical empiricist research consensus in his time. But because of its lack of articulation he failed to install a new one. In line with the spirit of the "new image of science" that Kuhn put forward, philosophers of science after SSR started to take more serious actual scientific practice. But the lack of generality of discipline-specific case-studies has led to a fragmentation of the discipline into philosophies of individual sciences. Kuhn himself later came to regret this emphasis on case-studies, calling them "misleading" because specific cases do not provide a basis for the extrapolation of general normative guidance, rather they illustrate their sheer variation. This variation has played a central role in philosophy of science from its inception, when Reichenbach and Carnap were struggling with the construction of alternative geometries. Too much variation threatens philosophy of science's ability to make general claims about science. And as for making normative recommendations for specific situations, dependent on thorough knowledge of an often partly tacit context, there is no reason to assume that philosophers have privileged access to this context over and above the scientists concerned. Reichenbach proposed that philosophers should refrain from making definite proposals but rather construct a map of possibilities that can be used by scientists who can, *given* their particular context, use it to find out what their commitments are. "It is a kind of logical signpost which we erect; for each path we give its direction together with all connected directions and leave the decision as to his route to the wanderer in the forest of knowledge" (Reichenbach 1938, 14). Different frameworks serve different purposes, and given a particular scientist's purpose this map will help them find the optimal framework. Just as biologists confronted with the diversity of species had done before Darwin: they explained away variation using a fixed set of purposes. But where do these purposes come from? Philosophers' self-imposed restriction to the context of justification effectively put this question outside of philosophy of science. As far as philosophers were concerned, the purposes were *given,* just as biologists before Darwin had assumed as given the purposes species serve. But like Darwin, Kuhn had realized from his empirical observations the large amount of variation in these purposes. So instead of using the purposes as an explanation for the variety of frameworks, he made that variety of purposes itself an explanandum. Although there is no general story to be told about particular purposes, he realized that there might still be a general pattern to be found in the process of their change: "many of the most central conclusions we drew from the historical record can be derived instead from first principles" (Kuhn 2000, 112), and these principles "are necessary characteristics of any developmental or evolutionary process" (ibid. 119). Kuhn's intervention can hence be understood as a Darwinian one: from different frameworks for different purposes to a realization that variation is the norm and general results can be found only in their patterns of change. Hence focus shifts from the products of science to its process. The components of a complex system cannot be understood exhaustively without taking into account their past and their relation to each other. A philosophy seeing science as a complex system therefore makes descriptive and normative claims about a new level of analysis, the *systemic* level. Even though traditional philosophy of science is increasingly fragmented because of the lack of generality of discipline-specific case-studies, a *systemic* philosophy of science might reveal that there is indeed an across-the-board story to be told about which philosophers of science can claim exclusive expertise.

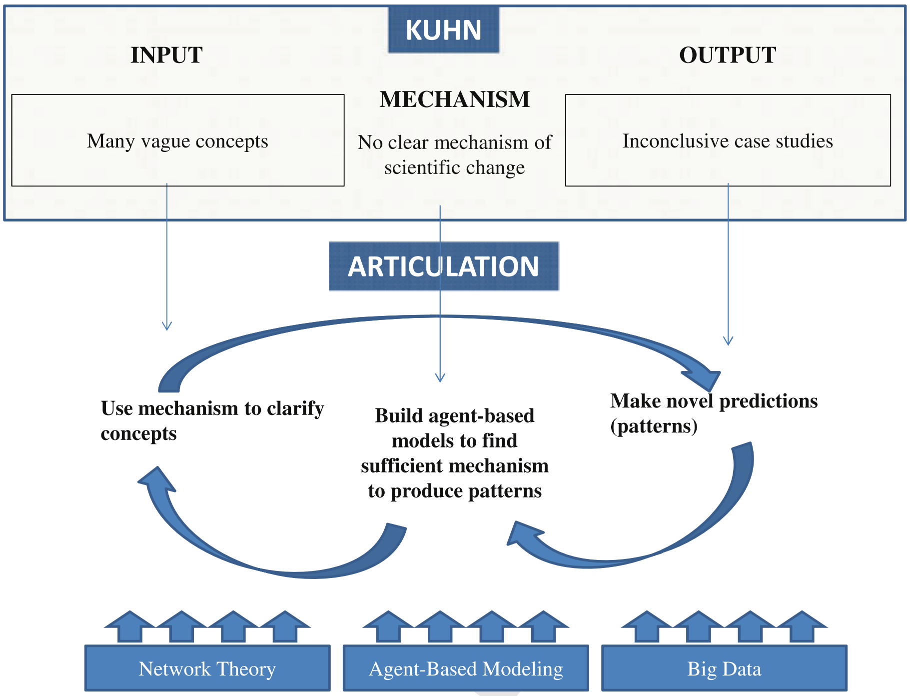

Fig. 2 A better articulation of the Kuhnian paradigm is a necessary condition for its operationalization

In the previous section I have sketched a number of substantial developments in the tools that can be used to articulate the Kuhnian paradigm. But the articulation of the Kuhnian paradigm should not be an end in itself. Rather the goal is to operationalize it: to make it constitutive of a research agenda for the philosophical investigation of science including both a descriptive and a normative component; it has to *describe* what science is, and *explain* why it works.

3.1 Descriptive: Science as a Process

Describing science as a complex system means science is essentially a process rather than just the sum of its parts. Traditional philosophy of science takes the finished products of science as a starting point and considers their change only in response to external factors. A Kuhnian philosopher of science takes a step back and wonders how possibly an even remotely coherent and successful body of knowledge can emerge from the localized interactions of individual scientists through time. This allowed Kuhn to thematize systemic, dynamic phenomena such as schools, paradigms and revolutions, phenomena emerging from the interactions of their components and not reducible to those components. Understanding these phenomena normally not considered part of the domain of philosophy of science requires understanding science as a *process* rather than as the sum of its products because they cease to exist when their components stop interacting and their current structure can only be understood as the result of the localized interactions of its components in the face of chance events through time. This is why Kuhn considers the historical, the social and the contingent to be integral parts of the domain of philosophy of science. Without them science could not be seen as a process. The benefits of describing science as a complex system are then twofold. First it extends the domain to a range of novel phenomena at the systemic level such as schools, paradigms and revolutions, and second it can do so without putting excessive demands on the individual agents in terms of the amount of information they can process and the amount of oversight they have.

The main descriptive challenge of the Kuhnian paradigm is then to describe these systemic features such as schools, paradigms, revolutions, disciplines and the power-law distribution of citations as emergent phenomena. If the domain of traditional philosophy of science is the question how science reacts to exogenous chance events such as new observations resulting from technological advances, the domain of Kuhnian philosophy of science is to investigate to what extent these are reinforced by and simultaneously change the self-organized structure of science. Why do some discrepancies become anomalies and others don't? Why do some solutions become exemplars and others not? Why do disciplines form? Why does disciplinary diversity persist? To what extent can these boundaries be explained by external properties of the subject matter, and to what extent are they self-organized? How can there be rational disagreement within disciplines? How possibly could something like a "paradigm" or a “revolution” occur? Both the suitability and the timeliness of using the above tools for these purposes is evidenced by the fact that physicists themselves have started using agent-based models based on network theory to model the emergence and decline of Kuhnian paradigms (Bornholdt et al. 2011).

Kuhn’s description was flawed by a lack of conceptual clarity, the lack of an explicit mechanism of change and the inconclusiveness of the adduced historical evidence. The new developments in the previous section now provide the means to overcome these descriptive flaws. Network theory offers an overview of a wide range of phenomena that can emerge on networks, along with explanations of how they can possibly emerge. Firmly rooted in mathematics and condensed-matter physics, it provides a precise and powerful conceptual framework for description. The resulting conceptual clarity is a necessary condition for programming agent-based models. An agent-based model is a computational model for simulating the interaction of autonomous agents to observe the behavior of the aggregate system. They can be used to provide how-possibly explanations for emergent structures. By canvassing possibility space, testable predictions can be made. The resulting hypotheses can then be tested against the new and vast set of empirical data available in scientometric datasets.

3.2 Normative

The shift in perspective that is brought about by seeing science as a complex system is that traditional philosophical problems are injected with the dimensions of interaction and time. A system with multiple agents allows them to be different, divide labor over them and let the sum of their labor be more than its parts. With the introduction of time comes a conflict between the past and the future: a choice can be designed to optimize on current knowledge, but can also be aimed at increasing the amount of knowledge in the future. This conflict between exploitation and exploration was thematized by Kuhn as the “Essential Tension” (1977). It is a direct consequence of a process-view on science and the key to understanding the philosophical implications of Kuhn’s perspective on science. Restricted to the finished products of science, the normative evaluation of scientists’ choices can be restricted to a static evaluation of the decision given the available information. However, if science is an ongoing process, scientists might choose to compromise on exploiting *existing* knowledge in favor of finding more knowledge in the *future*.

Rationality: In a situation that requires both exploration and exploitation, individual scientists are effectively faced with a so-called “multi-armed bandit” problem, after the model where a gambler enters a hall full of slot machines each with an unknown payoff matrix and has to trade off playing the same slot machine to get better information about its payoffs against exploring other slot machines that might have a more favorable payoff matrix. Theory *choice* becomes theory *search*. Scientists not only must choose the best current theory but also the one that is most likely to lead them to better theories in the future. For Kuhn, scientific rationality is not about adopting what is currently best, but about “the fittest way to practice future science” (SSR, 172). Scientific rationality goes from being backward-looking in the case of the evaluation of “finished” products, to being both backward-looking (exploitation) and forward-looking (exploration) in the case of practicing future science. Finding a dynamic balance between exploration and exploitation is a fundamental normative challenge for a systemic philosophy of science. Mayo-Wilson et al. (2012) use multi-armed bandit models to analyze theory choice.

Virtues: Because of the different nature of exploitation and exploration, it is natural to assume there are different (sets of) potentially conflicting virtues governing theory choice depending on whether one aims more at exploration or more at exploitation. For example the virtues of simplicity and generality are often contested, but then again they seem to play a crucial role in the exploration of new frameworks; see for example Einstein (1934) for a defence of the virtue of simplicity. This suggests they are explorative virtues, and their contestation can be explained by the fact that traditional philosophers only have room for exploitative virtues. The conflict between these virtues and how to deal with them (e.g. resulting in different strategies for model-building) is the subject of an old but still growing literature (Levins 1966; Orzack and Sober 1993; Matthewson and Michael 2009).

Division of Labor: If theory search involves both an exploitative and an explorative dimension and different (sets of) virtues are associated with it, it can be expected that some scientists are better at exploring and others at exploiting. Hence it is rational to divide labor over explorers and exploiters, or as is more common in the literature on the division of labor in science, between mavericks and followers (e.g. Kitcher 1990). A normative challenge that is still largely open is what an optimal mix of both would be, and if there is even a general answer to this question. Weisberg and Muldoon (2009) provide an exemplary treatment of this challenge. Kuhn moreover described how the aggregation of these individual actions leads to a striking pattern of balancing exploitation and exploration at the aggregate level, whereby entire disciplines can go into an exploitative mode during “normal science” and explore new frameworks during “revolutionary science”. Although this is a self-organized pattern, a normative challenge is to find out whether this is the most rational way to collectively trade off exploration and exploitation in a scientific community. An additional question is how such self-organization compares to so-called “pre-paradigmatic” situations where self-organization does not succeed.

Independence: In a complex system, individual-level properties do not necessarily carry over to the systemic level. Hence collective rationality does not require perfectly rational individuals, but individual rationality does not guarantee systemic rationality. This property is coined the “independence thesis” by Mayo-Wilson et al. (2011). The future-orientedness of theory choice makes perfect rationality in principle impossible because of the fundamental uncertainty (not just risk) associated with estimating the fruitfulness of a framework that still needs to be developed. This uncertainty is evidenced in the multi-armed bandit problem, where in most cases there is no unique strategy that can be proven to be optimal. Remarkably simple *rules of thumb* often outperform more complex strategies in these situations. It becomes then an important normative challenge for philosophers of science to determine what these rules of thumb should be. Kuhn himself admitted that he did not see how he could articulate how scientists following simple rules of thumb could together produce successful science.[2] The work of Gigerenzer et al. (2000) on simple heuristics that make us smart breaks new ground in this respect.

Progress: Complex systems need not have an endpoint and when they have it need not be optimal, making traditional linear notions of scientific progress inapplicable. Moreover as a result of dynamic interaction rules scientific practice changes the very rules by which it operates, leaving no independent yardstick to measure progress with. This problem is common to all complex adaptive systems; as Kuhn notes in the final pages of SSR, also for biological evolution. De Langhe (forthcoming) represents the problem of progress in a dynamic environment within the epistemic landscapes framework introduced by Weisberg and Muldoon (2009) as the discovery of a “dancing” landscape, drawing on existing formalism from models of dancing fitness landscapes in biology such as Bak and Sneppen (1993).

4 Conclusion

In recent decades there have been a number of major developments which should have a serious impact on our philosophical understanding of science. Vast new empirical, computational, and theoretical resources have become readily available. In this paper I have argued that Thomas Kuhn can offer a framework within which the philosophy of science can exploit these new resources. The examples that were given in the previous section illustrate that the exploitation of these new resources has already started, but in a fragmented way. The Kuhnian paradigm unifies these novel contributions under the heading of a systemic philosophy of science, of which they are exemplars. I strongly believe they are pointing in the direction of the fittest way to practice future philosophy of science.

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[2] “Even those who have followed me this far will want to know how a value-based enterprise of the sort I have described can develop as a science does, repeatedly producing powerful new techniques for prediction and control. To that question, unfortunately, I have no answer at all […] The lacuna is one I feel acutely” (Kuhn 1977, 332–333).

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