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An Agent-Based Model of Thomas Kuhn's *The Structure of Scientific Revolutions*

Rogier De Langhe [*]

Abstract: *»Thomas Kuhn's ‚Die Struktur wissenschaftlicher Revolutionen'. Eine agentenbasierte Simulation«*. Kuhn's Structure of Scientific Revolutions is interpreted as the specification of an agent-based model. Kuhn described scientists as autonomous agents and an emergent pattern of evolving paradigms. The missing link in his account is then a mechanism by which this pattern self-organizes from the interactions of autonomous scientists without centralized control. This paper exploits advances in agent-based modeling and stigmergy to fill the missing link in Kuhn's account. A complete agent-based model of Kuhn's Structure of Scientific Revolutions could lead to a better understanding of the contribution of the evolution of the social structure of science to its success.

Keywords: Paradigms, revolutions, rationality, agent-based modeling, Thomas Kuhn, stigmergy.

1. Kuhn's Lacuna

Thomas Kuhn's *Structure of Scientific Revolutions* (SSR) is not only one of the most popular, but also one of the most controversial works in 20th century philosophy. Based on historical evidence, Kuhn claimed in SSR that "There is no neutral algorithm for theory-choice" (Kuhn 1970, 200). An important consequence is that coordination among scientists is no longer straightforward. The challenge for Kuhn is to explain how scientists self-organize in order to aggregate results over scientists and cumulate them over time in the absence of a central authority.

Kuhn's alternative for central coordination by a universal scientific method was the concept of the "paradigm": local, endogenously emerging coordination on a number of shared commitments concerning what the puzzles are, how to solve them and what counts as an acceptable solution. However the paradigm concept is itself left unexplained *(How do paradigms emerge in the absence of centralized control?).* As a result many scholars concluded that paradigms are

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too vague to carry any substantial meaning (Shapere 1984; Scheffler 1982; Fuller 2001). The main argument for this line of criticism was that Kuhn himself seemed to be using the concept in different ways throughout the book. An analysis by Masterman (1970) revealed three different families of meanings for the paradigm concept in SSR: agents, rules, and products, or, in her terms, the "sociological," "metaphysical," and "artefact" paradigm.

This paper provides a mechanism for the emergence of paradigms from the interactions of autonomous scientists. This is facilitated by the fact that SSR can itself be seen as an early attempt at designing an "agent-based model" of a social system. As I intend to demonstrate in this paper, SSR can quite naturally be interpreted as the specification of an agent-based model. In hindsight, both Kuhn's description of scientists as autonomous agents (cf. section 2) and his description of an emergent pattern (cf. section 5) fit well within the agent-based paradigm. The agent-based perspective also unifies Kuhn's apparently inconsistent uses of the paradigm concept by interpreting them as different sides of the same coin, viz. phenomena emerging from rule-based interactions (rules) between autonomous agents (agents) leaving traces in the form of scientific papers (products).

An agent-based interpretation of Kuhn's work suggests that the controversy surrounding Kuhn's image of science is perhaps an effect not so much of its vagueness, but of its incompleteness. An agent-based model consists of three components: macroscopic patterns emerge from the local interactions of autonomous agents (Bonabeau 2002; Heath 2009). Kuhn only managed to provide two. The first edition of SSR focused on describing macroscopic patterns: preparadigmatic and mature science consisting of periods of normal science, crisis, and revolution. The book became popular but drew harsh criticism directed mainly at the apparent lack of rationality of Kuhnian scientists, e.g. Popper (1970) and Lakatos (1970). In response, Kuhn expanded on the role of individual scientists in science, mainly in a postscript to the book's second edition published in 1970 and in a later paper (Kuhn 1977). The criticism endured and after 1980 the term paradigm practically vanished from Kuhn's writing (Vondietze 2001). Kuhn never managed to provide the third component: an explicit mechanism by which the patterns he described self-organize from the interactions of autonomous scientists. This is a lacuna Kuhn himself was aware of.

> 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, 332-3)

Kuhn's lacuna is understandable. Apart from precursors such as Conway's Game of Life and the segregation model (Schelling 1978), the study of complex systems (Newman 2011), the agent-based paradigm and its application to social phenomena only came to fruition in the 1990s, with e.g. Holland (1991) and Gilbert (1999). This would explain why Kuhn, himself a condensed-matter physicist who had worked with precursors of agent-based models like the Ising-model (Ising 1925), was so often misunderstood in his time (Marcum 2015, 236). Also insight in the importance of stigmergic interactions for the self-organization of social structure was lacking in Kuhn's lifetime (Heylighen 2016).

But twenty years after Kuhn's death, the context has changed. The agent-based paradigm has developed further and insight into stigmergy has improved. In this paper I want to use these two recent advances to fill Kuhn's lacuna: a mechanism for understanding how paradigms emerge from the interaction of autonomous scientists without centralized control. This mechanism will be embodied in the agent-based model presented in this paper. Section 2 interprets Kuhnian scientists as autonomous agents. Section 3 searches for the stigmergic interactions in Kuhn's description of the process of science. These two components are combined into an agent-based model in section 4 in order to demonstrate in section 5 that they are sufficient to generate Kuhnian macroscopic dynamics. This constitutes, I argue, an agent-based model of Thomas Kuhn's Structure of Scientific Revolutions.

2. Scientists as Autonomous Agents

If SSR is interpreted as the specification of an agent-based model, Kuhnian scientists must be interpreted as "agents." Kuhn's characterization of individual scientists was very controversial at the time. In their first reactions, Kuhn's contemporaries focused on the idea that scientists are dogmatic specialists with little interest in novelty. Paul Feyerabend wrote a paper "Consolations for the specialist" in which he rejected what he considered to be an ideology that "could only give comfort to the most narrowminded and the most conceited kind of specialism" (Feyerabend 1970, 197-230). Popper wrote a paper "Normal science and its dangers" in which he states:

> In my view the "normal" scientist, as Kuhn describes him, is a person one ought to be sorry for. [He] has been badly taught. He has been taught in a dogmatic spirit: he is a victim of indoctrination. (Popper 1970, 52-3)

Kuhn's most contested claim is that scientific values (such as fruitfulness, accuracy, and precision) are not sufficient to solve the problem of paradigm choice: "They are not by themselves sufficient to determine the decisions of individual scientists" (Kuhn 1977, 358). The values function not as algorithms because the values are contingent, subjective, and conflicting. According to Kuhn, paradigm choice is ultimately a matter of "faith." To Kuhn's own horror, many scholars concluded that Kuhn thought science was just a matter of "mob psychology" (Lakatos 1970, 178) or "a political and propagandistic affair"

(Laudan 1977, 4). Kuhn denied this: "It is emphatically not my view that adoption of a new scientific theory is an intuitive or mystical affair, a matter for psychological description rather than logical or methodological codification" (Kuhn 1970, 157).

But how can these inconclusive values then account for the success of science? To this Kuhn admits to have only a "very partial and impressionistic" (Kuhn 1970, 152) answer. Because it is "about argument and counterargument in a situation in which there can be no proof, our question is a new one, demanding a sort of study that has not previously been undertaken" (Kuhn 1970, 152). His characterization of that new sort of study anticipates the use of agent-based models for the study of social systems:

> We must learn to ask this question differently. Our concern will not then be with the arguments that in fact convert one or another individual, but rather with the sort of community that always sooner or later re-forms as a single group. (Kuhn 1970, 153)

In fact, Kuhn even tried to program such an agent-based model himself. "I am currently experimenting with a computer program designed to investigate their properties at an elementary level" (Kuhn 1970, 191-2). Andersen (2000, 225) later evaluated this attempt:

> He wanted to develop a computer program that would simulate a non-rule-governed transmission of concepts from one generation to the next. This effort was hampered by the lack of empirical psychological research and by the limitations of programming methods and machines.

In sum, despite Kuhn's best efforts, many of his readers took him to describe scientific behavior as contingent, subjective, conflicting, and dogmatic. I argue in here that a solution to Kuhn's problem is available now that the agent-based approach in computer science is better developed (see Bandini [2009] for an overview). According to one of the most widely used definitions (Woolridge 1995), intelligent agents interact with their environment and with each other based on their own goals and behaviors which they can modify in reaction to current or anticipated changes in those circumstances. Intelligent agents are autonomous, social, situated, and proactive. Interpreting Kuhnian scientists as autonomous agents puts Kuhn's claims about scientists in a different and much less controversial perspective. A perspective that makes it intelligible how such scientists can produce successful science as we know it. From this perspective, scientific behavior is not contingent but autonomous, not dogmatic but social, not subjective but situated, not conflicting but adaptive.

- Autonomy: From an agent-based interpretation, statements that choice can never be fully determined by an algorithmic scientific method ("They are not by themselves sufficient to determine the decisions of individual scientists" [Kuhn 1977, 358]) suggest not contingency or a lack of rationality on the part of scientists, but their autonomy. This autonomy of the agents is the reason why agent-based models are stochastic rather than deterministic. These models do not idealize non-epistemic factors away but incorporate them as randomness. Autonomy allows agents to change decisions depending on characteristics of the environment. And since these characteristics can be assumed to be randomly distributed, randomness can account for autonomy. Kuhn also notes the importance of random contextual factors such as “idiosyncrasies of autobiography and personality” (Kuhn 1970, 153) and it explains why for Kuhn agent behavior is not defined by strict rules (“There is no neutral algorithm for theory-choice” Kuhn 1970, 200), but rather guided by heuristic rules of thumb, viz. “criteria that influence decisions without specifying what those decisions must be” (Kuhn 1977, 330).

- Social: Smart agents take into account the actions of others. Communication and coordination with others is a condition of possibility for the aggregation of results over scientists and accumulation over time. Successful, specialized science requires a high level of social coordination in order to allow for a division of cognitive labor. Without coordination, cooperation would be all but impossible. Paradigm debate “is about premises, and its recourse is to persuasion as a prelude to the possibility of proof” (Kuhn 1970, 199). On the other hand, taking into account the actions of others can also be required to spread risk (Kuhn 1970, 186). This essential tension is developed further in the next section.
- Reactivity: Agents are situated in a specific context and their behavior must change if that context changes. For this reason two equally smart scientists might make different decisions in different contexts. Kuhn often makes this point quite literally. There is “no systematic decision procedure which, properly applied, must lead each individual in the group to the same decision” (Kuhn 1970, 200). Similarly: “When scientists must choose between competing theories, two men fully committed to the same list of criteria for choice may nevertheless reach different conclusions” (Kuhn 1977, 324), and “individuals may legitimately differ about their application to concrete cases” (Kuhn 1977, 357).
- Pro-activity: Agents are not backward-looking but forward-looking. Scientists do not want to know what was the best paradigm in the past, but what will be the best one to make contributions to in the future. Paradigm choice is choosing “the fittest way to practice future science” (Kuhn 1970, 172). That is because „paradigm debates are not really about relative problem-solving ability [...] the issue is which paradigm should in the future guide research on problems many of which neither competitor can yet claim to resolve completely [...] [T]hat decision must be based less on past achievement than on future promise” (Kuhn 1970, 157-8).

3. Stigmergic Interactions

The previous section has shown that Kuhn provides an (especially for that time) quite explicit characterization of scientists as autonomous agents. Although his historical case-studies allowed him to describe individual cases of how these scientists manage to self-organize into paradigms, he apparently lacked a theoretical concept that would allow him to pick out and generalize the essential aspects of this process. Thanks to the study of termites (Grasse 1959) and ant colonies (Sumpter 2003) a theoretical concept has become available to explain coordination in social systems without centralized control: *stigmergy*. Ant colonies manage to perform complex, coordinated tasks without central supervision or direct communication by leaving traces that other agents respond to. Stigmergy depends on feedback loops by which autonomous agents influence each other's behavior indirectly, through traces in the environment. As such "Stigmergy allows global coordinated activity to emerge out of local, interdependent actions" (Heylighen 2016). Positive feedback loops promote successful behavior, negative feedback loops dampen errors. These virtuous and vicious cycles can explain the remarkable effectiveness of very diverse phenomena such as termite hill, a network of trails, or even a world encyclopedia (Heylighen 2007).

In this paper I use an agent-based model to apply this framework to Kuhn's early work (before 1980). Agents are scientists. The traces scientists leave in the environment are scientific papers. Emergent patterns are preparadigmatic and mature science (normal science, crisis, and revolution). The key to filling the missing link in Kuhn's account is identifying the stigmergic interactions. In what ways does the contribution of a scientist to a paradigm affect the probability of others making a contribution to that paradigm? Kuhn's SSR contains two important feedback loops: a positive feedback loop through adoption of the paradigm and a negative feedback loop through production to the paradigm. I will show in section 5 that these stigmergic interactions between autonomous scientists are sufficient for the emergence of Kuhnian macroscopic patterns.

3.1 Increasing Returns to Adoption

Kuhn argues that paradigms allow science to advance in much the same way as Adam Smith had argued centuries earlier that assembly lines allow the economy to advance. Workers increase productivity by coordinating on a standard for the division of labor. Coordinating on fundamentals allows them to learn faster, work harder, and develop more specialized tools.

> This great increase of the quantity of work which, in consequence of the division of labour, the same number of people are capable of performing, is owing to three different circumstances; first, to the increase of dexterity in every particular workman; secondly, to the saving of the time which is commonly lost

> in passing from one species of work to another; and lastly, to the invention of a great number of machines which facilitate and abridge labour, and enable one man to do the work of many. (Smith 1776, 4)

Compare this to Kuhn's description:

> [The Franklinian paradigm] suggested which experiments would be worth performing and which, because directed to secondary or to overly complex manifestations of electricity, would not. Only the paradigm did the job far more effectively, partly because the end of interschool debate ended the constant reiteration of fundamentals and partly because the confidence that they were on the right track encouraged scientists to undertake more precise, esoteric, and consuming sorts of work. Freed from the concern with any and all electrical phenomena, the united group of electricians could pursue selected phenomena in far more detail, designing much special equipment for the task and employing it more stubbornly and systematically than electricians had ever done before. Both fact collection and theory articulation became highly directed activities. The effectiveness and efficiency of electrical research increased accordingly. (Kuhn 1970, 18)

This coordination effect results in increasing returns to adoption of a paradigm. The more scientists contribute to the same paradigm, the more opportunities for specialization by dividing cognitive labor. This is a first stigmergic interaction. When a scientists publishes a paper in a paradigm, that scientist's adoption will increase the probability of other scientists adopting the same paradigm. Kuhn provides an explicit description of this feedback loop by which more adopters to a paradigm improve the paradigm, in turn attracting more adopters:

> At the start a new candidate for paradigm may have few supporters, and on occasions the supporters' motives may be suspect. Nevertheless, if they are competent, they will improve it, explore its possibilities, and show what it would be like to belong to the community guided by it. And as that goes on, if the paradigm is one destined to win its fight, the number and strength of the persuasive arguments in its favor will increase. More scientists will then be converted, and the exploration of the new paradigm will go on. Gradually the number of experiments, instruments, articles, and books based upon the paradigm will multiply. Still more men, convinced of the new view's fruitfulness, will adopt the new mode of practicing normal science, until at last only a few elderly hold-outs remain. (Kuhn 1970, 159)

The importance of increasing returns to adoption of standards (and the complex dynamics in which this positive feedback loop results) only became the subject of systematic study in economics as part of the "increasing returns revolution" in the 1990s (Arthur 1989; Krugman 2009).

3.2 Decreasing Returns to Production

Coordinating on fundamentals increases the benefits from specialization. However this necessarily goes at the cost of the diversity of fundamental assumptions explored: "the price of significant scientific advance is a commitment that runs the risk of being wrong" (Kuhn 1970, 101). As with an assembly line, the standardization of assumptions is the necessary price to pay for the economies of scale it enables.

> Specialization and the narrowing of the range of expertise now look to me like the necessary price of increasingly powerful cognitive tools. What's involved is the same sort of development of special tools for special functions that's apparent also in technological practice. (Kuhn 2000, 98)

A crucial problem is that once a paradigm is chosen it is impossible to create novelty. As such Kuhn writes that "Normal science does not aim at novelties of fact or theory and, when successful, finds none" (Kuhn 1970, 52). This is because choosing a paradigm requires knowledge, but a condition for that knowledge is the very paradigms at issue:

> [C]hoice [...] between competing paradigms [...] is not and cannot be determined merely by the evaluative procedures characteristic of normal science, for these depend in part upon a particular paradigm, and that paradigm is at issue. (Kuhn 1970, 94)

This problem of the impossibility of novelty, known since Antiquity as the Meno problem, is a common occurrence in models of innovation. For example technology adopters have a tendency to lock-in to potentially suboptimal technological standards (Arthur 1994; David 1985). It is typically solved by introducing evolutionary dynamics in the form of a feedback loop (Nickles 2003). In Kuhn's work there is such a feedback loop from the knowledge produced within the paradigm back to the paradigm that made that knowledge possible. Kuhn writes that "[Paradigms] are directed not only to nature but also back upon the science that produced them" (Kuhn 1970, 103) and claims that there is "a feedback loop through which theory change affects the values which led to that change" (Kuhn 1977, 336). This is the second stigmergic interaction: a contribution to a paradigm will decrease the probability of another agent contributing to that paradigm. As a consequence, novelty can emerge: "research under a paradigm must be a particularly effective way of inducing paradigm change" (Kuhn 1970, 52) and "the ultimate effect of this tradition-bound work has invariably been to change the tradition" (Kuhn 1977, 234).

> This constitutes a second stigmergic interaction found in Kuhn's description of the process of science. When a scientists publishes a paper in a paradigm, the number of fruitful research opportunities left in that paradigm is gradually exhausted. The marginal value of an extra unit produced within a paradigm decreases with production. This tendency has long been known in economics as "the law of diminishing marginal utility". (Gossen 1983)

4. Agent Based Model

This is a model[1] of scientists publishing papers. Publishing a paper (or leaving a “trace”) involves both the production of a paper and the adoption of a set of paradigmatic assumptions underlying that paper. In the previous section it was shown that adoption and production both affect other agents’ behavior through two different stigmergic feedback loops. More adopters imply more opportunities for specialization. But more production implies fewer opportunities left for fruitful research. The former increases the probability of agents adopting the paradigm, incentivizing the exploitation of the existing paradigm (tradition); the later decreases it, incentivizing the exploration of new paradigms (innovation). Kuhn called this conflict between tradition and innovation (Kuhn 1959) the “essential tension” in science. This tension makes it possible to capture network externalities without the risk of lock-in to a potentially suboptimal equilibrium (Arthur 1989; Leydesdorff 2001). In the next section I show that this essential tension is sufficient for Kuhnian dynamics to self-organize at the macrolevel. Here I use it to specify how agents decide whether to exploit or explore. The model is hence driven by agents facing the essential tension at each turn.

How do scientists decide whether to exploit or explore? For Kuhn, adopting or abandoning a paradigm is not just a matter of encountering discrepancies between theory and fact. Such discrepancies are the puzzles the paradigm provides to scientists as fruitful research opportunities. It is only when scientists no longer believe that the resources the paradigm provides will suffice to solve those puzzles, that puzzles become anomalies (Kuhn 1970, 81-2). One can never be certain that something will never be found, as such this decision is ultimately a matter of “faith.” For scientists to lose faith, they need to be converted by others adopting different paradigmatic assumptions. “We must therefore ask how conversion is induced and how resisted” (Kuhn 1970, 152).

Faith is “the assurance that the older paradigm will ultimately solve all its problems, that nature can be shoved into the box the paradigm provides” (Kuhn 1970, 151-2). In the previous section it was shown that, ceteris paribus, the fruitfulness of future research opportunities in a paradigm increases with adoption and decreases with production. As a consequence, the two stigmergic interactions in the previous section can be used to quantify faith in terms of adoption and production. This makes possible a precise specification of agents’ probability of conversion.

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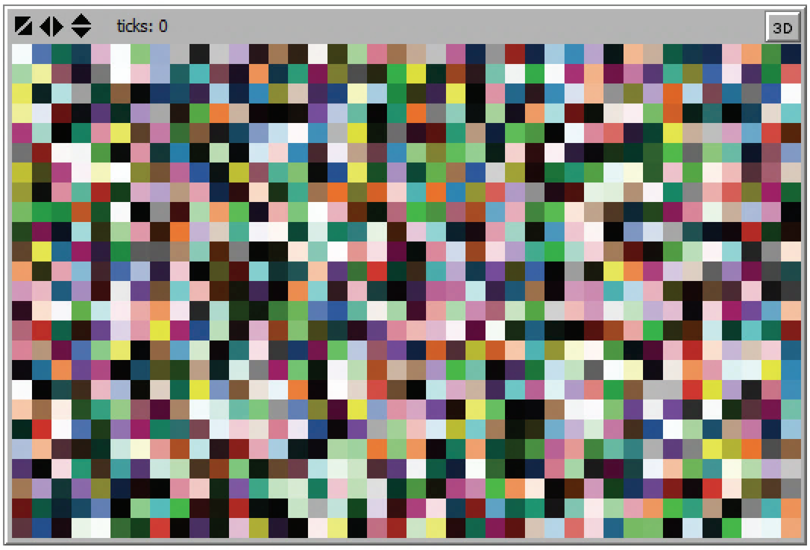
[1] The model was written using the *Netlogo* software package version 4.1.3 and can be downloaded here: <https://www.openabm.org/model/5187/> (Accessed December 5, 2017).

4.1 Model Specification

Figure 1: Initial State of the Model



Consider an $n \times n$ toroidal grid consisting of $N = n^2$ patches (Figure 1). Each patch represents a scientist. Scientists do not move and have eight (Moore) neighbors. Each scientist publishes one paper every turn. Publishing a paper requires the adoption of a set of (implicit or explicit) *paradigmatic assumptions* $S(s_1, \ldots, s_M)$ about what are meaningful questions, what is relevant data, what are convincing arguments and what counts as a sufficient solution. The number of agents N is a constant of the system, M varies endogenously. The paradigmatic assumptions adopted by the agent/patch are represented by the color of that patch. Changes in the colors of the patches thus represent the dynamics of adoption of paradigmatic assumptions. In the initial state of the model there are as much paradigmatic assumptions as there are scientists. Paradigmatic assumptions are not yet paradigms. A *paradigm* only emerges when multiple scientists coordinate on the same paradigmatic assumptions. Paradigms can be recognized in the model as clusters of patches with the same color.

Each turn each agent tries to persuade one of its neighbors (the target) to adopt its paradigm. An agent's persuasive power and a target's resistance to persuasion can be expressed as a function of the faith they have in their respective paradigm. This "faith" F is proportional (autonomy) to the value of the next (pro-activity) contribution to it. As a result of the stigmergic interactions with others (social), that value is proportional to the number of current adopters (adoption A) plus its own potential adoption, and negatively proportional to the total number of contributions made within the same paradigmatic assumptions (production *P*) plus its own potential contribution. Because agents are situated in a particular context (reactivity), I will assume scientists only have knowledge about adoption and production to their own paradigm and within their own Moore-neighborhood.

$$F_s(t) = \frac{(A_s(t)+1)^{\alpha}}{P_s+1} \quad (1)$$

The function of paradigms in science is to allow scientists to capture the benefits of specialization. The extent to which it does (and not its content) can be interpreted as the intrinsic value of the paradigm. The parameter α represents this intrinsic value. It represents the increasing returns to adoption that can be captured by adopting the same paradigmatic assumptions. The assumption of increasing returns to adoption corresponds to assuming that $\alpha > 1$. In this paper α is exogenous, interpreted as a domain-specific parameter (different domains in science allow for different levels) whereby the model represents a domain in science and all paradigms in the same domain have the same α. A useful extension of the model could be to make this parameter paradigm-specific to investigate under what circumstances paradigms with higher intrinsic value emerge.

It follows from equation 1 that faith in any novel set of paradigmatic assumptions (for which both adoption and production are 0) is always 1 irrespective of the value of α. This powerful feature of the model results in a non-zero probability of the occurrence of novelty and hence endogenizes the number of paradigms in the model.

Definite probabilities can now be assigned to the outcome of conversion attempts between an agent (the persuader) trying to persuade another agent (the target) to adopt its paradigm the next turn. The probability of conversion is proportional to the faith the converter and the target have in their respective paradigms and in the creation of a novel one. The more faith a persuader has in its paradigm, the stronger its persuasive power. Conversely, the more faith the target has in its paradigm, the stronger its resistance to conversion. The probability of a new set of paradigmatic assumptions being created is inversely proportional to both. As a result, new paradigms are created endogenously and communities will self-organize to find a dynamic balance between exploiting existing paradigms (specialization) and creating new ones (innovation).

A conversion attempt by a persuader trying to convert a target to adopt the set of paradigmatic assumptions s_i to s_j has three possible outcomes that can now be assigned precise probabilities:

Conversion (c): the target adopts the same paradigm as the persuader.

$$\mathrm{P_c} = \frac{\mathrm{F}_{\mathrm{s_i}}}{\mathrm{F}_{\mathrm{s_i}}+\mathrm{F}_{\mathrm{s_j}}+1} \quad (2)$$

Failed conversion (r): the target remains faithful to its previous paradigm.

$$\mathrm{P_r} = \frac{\mathrm{F}_{\mathrm{s_j}}}{\mathrm{F}_{\mathrm{s_i}}+\mathrm{F}_{\mathrm{s_j}}+1} \quad (3)$$

Novelty (n): the conversion attempt results in the target adopting a novel set of paradigmatic assumptions.

$$P_n = \frac{1}{F_{s_i} + F_{s_j} + 1} \qquad (4)$$

Note that the underlying model of rationality in this model is not of scientists as optimizers, but scientists as satisficers. As is often the case in evolutionary models, agents do not decide what option to choose, but what option to abandon. As such, as in evolution, they do not move toward anything, but away from a something that has become unsatisfactory. So the model does not determine what choice is made, but when a previous choice is abandoned. The model specifies not what new paradigm scientists will choose, but when they will abandon it. As I have explained in detail in De Langhe (2012) and De Langhe (2013), Herbert Simon's notion of satisficing is a natural fit as an account of Kuhnian rationality. It captures not only Kuhn's reference to theory choice as driven by rules of thumb rather than an algorithm (cf. supra), but also the fact that the characterization of the resulting evolutionary process as "a process that moved steadily *from* primitive beginnings but *toward* no goal" (Kuhn 1970, 172). For Simon, what counts as satisfactory is determined by an "aspiration-level mechanism." In this paper, this is the notion of "faith" is the aspiration-level mechanism. Basically, a paradigm is adopted until scientists "lose faith."

5. The Emergence and Decline of Paradigms

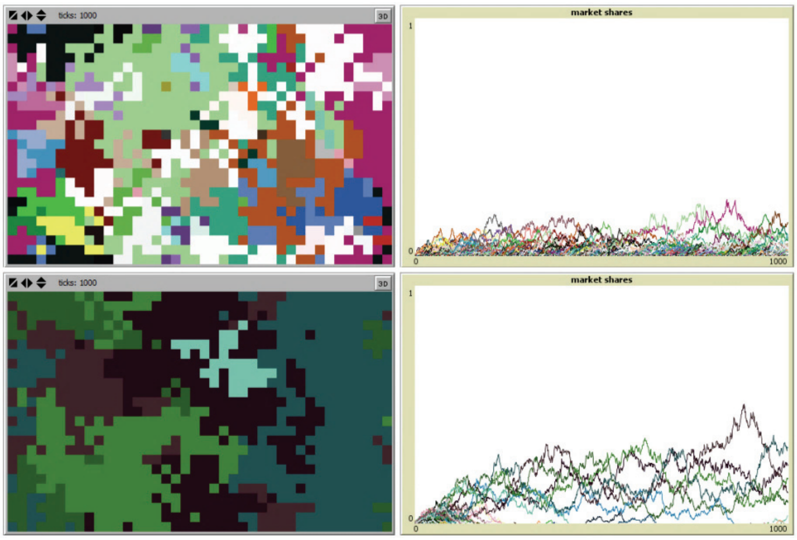
According to Kuhn, the evolution of the social structure of science contributes to its success in two apparently conflicting ways: both the emergence (paradigms for specialization) and decline (revolutions to innovate the paradigm itself) of coordination on paradigmatic assumptions can be progressive. Kuhn called this apparent conflict the "essential tension" between tradition and innovation. The dilemma whether to exploit an existing paradigm or to explore a new one presents itself both at the individual level and the community level. "Very often the successful scientist must simultaneously display the characteristics of the traditionalist and of the iconoclast" (Kuhn 197, 227). But it also emerges at the macro-level where mature science exhibits "a succession of tradition-bound periods punctuated by non-cumulative breaks" (Kuhn 1970, 208). The challenge for an agent-based model of SSR is twofold. First it must integrate both forces in the same model and then show how this tension at the microlevel gives rise to a similar pattern at the macrolevel: "we must seek to understand how these two superficially discordant modes of problem solving can be reconciled both within the individual and within the group" (Kuhn 1970, 239). In the previous section I have already characterized the local interaction rules for scientists to decide whether to exploit or explore at the individual level. In this section I meet both challenges by showing how a pattern of normal science punctuated by periods of crisis and revolution emerges from the interactions of autonomous scientists facing the essential tension. This is not straightforward:

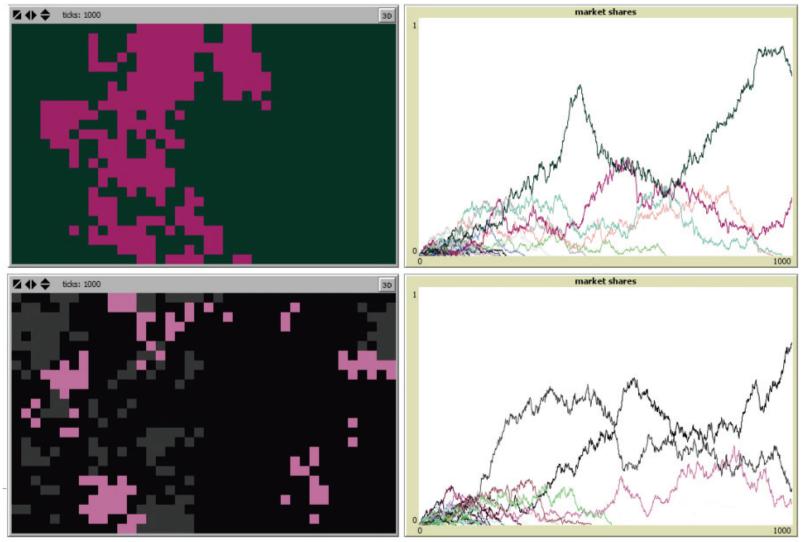
> [S]tudents of the development of science, whether sociologists or philosophers, have alternately been preoccupied with explaining consensus in science or with highlighting disagreement and divergence. Neither approach has shown itself to have the explanatory resources to deal with both. (Laudan 1984, 3)

If paradigms are standards for the division of cognitive labor, then an increase in α should result in the emergence of paradigms. To test this, I will treat α as an exogenous variable and observe the patterns emerging from the model for various values of α.

To give a sense for the dynamics of the model, Figure 2 shows typical behavior of the model for a population of 1,000 scientists for various values of α. A number of observations can already be made. Coordination among scientists over paradigmatic assumptions (viz. paradigms) emerge, move, decline, split up, and disappear again. The structure of the community changes as α increases. The number of paradigms decreases as the benefits from specialization (α) increase. Although these patterns appear to live a life of their own, they nevertheless emerge exclusively from the local interactions of intelligent agents based on their locally available information.

Figure 2: Typical Run of the Model

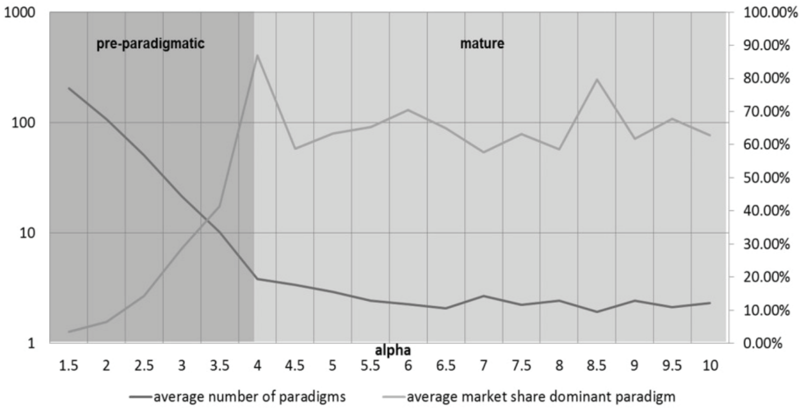




On the left, typical run of the model after 1,000 turns; on the right, evolution of market share throughout the run. Both for (from the top down) α= 2.5, α = 5, α = 7.5 and α = 10. N = 1,000.

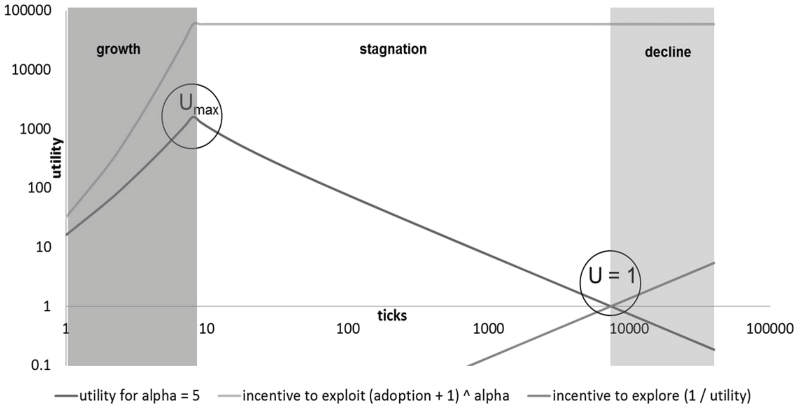
Possibility space for α is systematically explored in Figure 3. With a low α, there are a large number of paradigms each of which has low market share. There are almost as much paradigmatic assumptions in the community as there are scientists. This changes as α increases. The number of paradigmatic assumptions in the community decreases and their adoption increases. Paradigms start to emerge. Interestingly, this correlation disappears once α reaches a value of about 4, after which a further increase in α has no further effect on community structure. As such there are two stages to be distinguished. One stage reflecting what Kuhn calls the *pre-paradigm* stage in which "there is a multiplicity of competing schools [...] in which the results of their enterprise do not add up to science as we know it" (Kuhn 1970, 163) and *mature* science in which "the successive transition from one paradigm to another via revolution is the usual developmental pattern'" (Kuhn 1970, 12). The model makes it possible to make a precise distinction between both stages based on whether or not a change in α affects community structure. Robustness analysis shows that this result is independent of the size of the community.

Figure 3: Pre-Paradigmatic and Mature Science



Average number of paradigms (left axis) and the average market share of the dominant paradigm (right axis) after 2,000 turns averaged over three runs for a population of 1,000. Averages are calculated based only on the last 1,000 turns in order to make the figure representative of the typical state of the model after it has settled.

Figure 4: Evolution of Value of a Paradigm ($\alpha = 5$)



Why does the number of paradigms and their market share in mature science reach a ceiling, but not that of the entire community? This is because once at 4, a dominant paradigm is firmly in place but is still getting replaced occasionally by another one. In other words, the system avoids lock-in to a single paradigm. To demonstrate why this is the case, Figure 4 plots the evolution of the value of a mature ($\alpha > 4$) paradigm in isolation as adoption first gradually rises to 8 (=

the full Moore neighborhood) and then stays at 8, all the while adding to production.

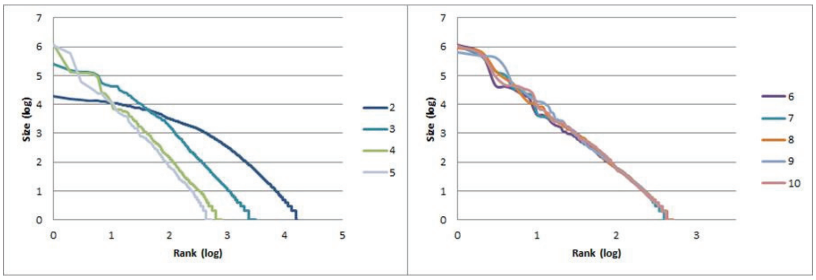
Figure 4 shows the lifecycle of a paradigm. It consists of three phases: growth, stagnation, and decline. The phases are marked by different shades of grey. The three phases are separated by two points: the point at which the expected value to a contribution reaches its maximal value U_{max} and the point at which it reaches the value 1 ($U = 1$).

- During the *growth* phase, the expected value of a contribution to the existing theory increases as more scientists adopt the theory and production has only just begun. Adoption is self-reinforcing because every new adopter increases the probability of adoption and the exhaustion of the paradigm resulting from production is not yet sufficient to offset it. At the end of this phase, the comparative value of a contribution to the existing theory is at its highest and the probability that new theories will be created at its lowest. But adoption-led growth cannot continue forever because of the finite size of the neighborhood, in this case the Moore-neighborhood.
- The *stagnation* phase begins when the increase in adoption stops but production continues. The value of a contribution to the existing theory decreases but remains superior because of the benefits of high adoption. Scientists breaking away from the pack and starting on new paradigmatic assumptions will be fighting the odds because their new paradigm offers opportunities for contributions of lower value, making it difficult to convince others to join them and start reaping the benefits of specialization together.
- A turning point is reached when sooner or later the necessarily decreasing value of contributing to the existing theory becomes smaller than *1* and those breaking away from the pack will be able to motivate adopters of the existing theory to join them with contributions of higher value. Quantitatively speaking, at every turn the probability of adopting a new set of paradigmatic assumptions is now higher than adopting the initial set. Every adopter gained for the new theory is one lost for the existing theory. This initiates the *decline* phase because breaking away from the pack is no longer dampened but reinforced. It is only a matter of time before one of the new theories gains prominence and replaces the existing theory.

The three-phase lifecycle is very robust. Except for very small systems, the benefits of adoption always outweigh the cost of production in the short term. However in the long term there will always be a point at which the benefits of adoption are offset by the cost of production. This follows analytically from the fact that adoption is finite (size of neighborhood) while production is infinite. All paradigms will perish eventually.[2]

If paradigms are a state of coordination among agents over paradigmatic assumptions, a revolution is the dissolution of this state. “Rather than a single group conversion, what occurs is an increasing shift in the distribution of professional allegiances” (Kuhn 1970, 158). A size distribution of revolutions can be obtained by looking at the distribution of maximal size of each paradigm. Since all paradigms perish eventually, this distribution reflects the size in the shift of professional allegiance brought about by the paradigm after its peak, and hence the distribution of revolutions. SSR gives the impression that revolutions always involve the entire community. In the postscript to the second edition, Kuhn provides some more detail about the size distribution of revolutions. He claims that it was never his intention to suggest that revolutions are total. Rather he maintains that revolutions of any size can occur and that most of them are actually quite small (Kuhn 1970, 180-1).

Figure 5: Rank-Size Distribution of Paradigms for Various Values of α



Plotting the rank-size distribution of paradigms in the model reveals that this is a very robust feature of the model. Figure 5 shows the rank-size distribution of paradigms for $N = 1{,}000$ after 2,000 turns for various values of α. Revolutions of all sizes occur, with small revolutions being the most likely. Robustness analysis has shown that these distributions are robust against the length of the simulation and the size of the community. As far as α is concerned, again the pattern occurs that differences in distribution occur as a result of changes in α only for pre-paradigmatic science and not once the science has matured ($\alpha > 4$).

6. Conclusion

In this paper I have shown that Kuhn’s *Structure of Scientific Revolutions* can be interpreted in a coherent way as the specification of an agent-based model.

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[2] This result could be called a “pessimistic meta-deduction.”

From this perspective, Thomas Kuhn, himself a condensed-matter physicist at Harvard under the Nobel prize winning physicist Van Vleck before turning philosopher, can be seen as one of the pioneers in attempting to apply insights from complex systems in physics to the social world (Newman 2011). I have interpreted SSR as an account of how scientists as autonomous agents coordinate on paradigmatic assumptions in the absence of centralized control to self-organize into "paradigms." The key to this interpretation has been to identify Kuhnian scientists as autonomous agents and to isolate in Kuhn's description of the process of science the stigmergic processes responsible for self-organization in scientific communities. These stigmergic processes were modeled in an agent-based model and shown to cause both the rise from preparadigmatic to mature science and within mature science the emergence and decline of paradigms.

Kuhn's project is important because it suggests a middle ground between philosophers of science and sociologists (Wray 2005, 154-5). Whereas philosophers of science have traditionally focused on the properties of successful science and sociologists on descriptions of the social structure of science, Kuhn's account implies that the evolution of the structure of scientific communities contributes to the success of science (Kuhn 1970, 8-9). This is because in Kuhn's perspective the emergence and evolution of coordination is a condition of possibility for successful science.

Far from reducing science to convention, Kuhn has rather suggested that there might be a link between the organization and the progress of science. Not only is this a claim that hardly sounds controversial from modern management perspective, but also the tools for investigating it empirically have become available in recent years thanks to the digitization of science. This is a project Kuhn explicitly anticipated already in 1962 at a time in which scientometrics and agent-based modeling were still largely undeveloped: "I take it that the job can and will be done" (Kuhn 1970, 178). It is this project of which this paper is but one component. In De Langhe (2017) I outline how the model presented in this paper can be integrated with scientometric data to provide a basis for an evidence-based framework of a normative macrostudy of science.

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