Self-Organization, Competition, and Succession in the Dynamics of Scientific Revolution

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Abstract
What is the relative importance of structural versus contextual forces in the birth and death of scientific theories? We describe a dynamic model of the birth, evolution, and death of scientific paradigms based on Kuhn’s *Structure of Scientific Revolutions*. The model creates a simulated ecology of interacting paradigms in which the creation of new theories is stochastic and endogenous. The model captures the sociological dynamics of paradigms as they compete against one another for members. Puzzle solving and anomaly recognition are also endogenous. We specify various regression models to examine the role of intrinsic versus contextual factors in determining paradigm success. We find that situational factors attending the birth of a paradigm largely determine its probability of rising to dominance, while the intrinsic explanatory power of a paradigm is only weakly related to the likelihood of success. For those paradigms that do survive the emergence phase, greater explanatory power is significantly related to longevity. However, the relationship between a paradigm’s ‘strength’ and the duration of normal science is also contingent on the competitive environment during the emergence phase. Analysis of the model shows the dynamics of competition and succession among paradigms to be conditioned by many positive feedback loops. These self-reinforcing processes amplify intrinsically unobservable micro-level perturbations in the environment – the local conditions of science, society, and self faced by the creators of a new theory – until they reach macroscopic significance. Such dynamics are the hallmark of self-organizing evolutionary systems.

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Introduction

Thomas Kuhn’s *Structure of Scientific Revolutions* heralded a radically new conception of science. In the traditional view science applies universally-accepted norms of logical inquiry and scientific development is seen as the cumulative triumph of ever more truthful and encompassing images of reality. In contrast, Kuhn argued that new theories replace old ones rather than building upon them, revolutionizing science’s very image of itself.¹ For Kuhn (and others)² scientific development is fraught with errors, blind alleys, and intense competition among competing world-views. Science proceeds ‘as a succession of tradition-bound periods punctuated by non-cumulative breaks.’³

The idea that social, historically contingent factors play a role in scientific development equal to or even greater than that of a theory’s intellectual content has elated many social scientists and historians as much as it has infuriated many philosophers and scientists.⁴ For many social scientists Kuhn’s theory legitimated resistance to the century-old attempt to make the study of society, politics and culture more like Newtonian physics. For others Kuhn’s attempt to historicize the scientific process was at best reckless and at worst heresy. Yet whether as prophecy or apostasy, his ideas continue to stimulate vigorous debate about the evolution of science.⁵ Why is it that some paradigms last for centuries while others quickly wither? How do intellectual, structural and contextual forces interact to shape and constrain the development of new paradigms?

We address these questions with a formal dynamic model of paradigm emergence and competition. The model creates a simulated ecology of interacting paradigms in which the genesis of new paradigms is stochastic and endogenous. The model captures the sociological dynamics of paradigms as they compete against one another for members, formulate and solve ‘puzzles’, recognize and react to anomalies. Competition for membership and resources is explicit. The model is used to investigate the relative importance of internal versus contextual factors in determining the fate of new paradigms.⁶

Although the model is based on Kuhn’s work we do not claim to have fully captured his theory. Translating the theory from its qualitative, highly abstract written form into an internally consistent,
formal model has involved simplifications and the introduction of auxiliary hypotheses. Nonetheless, formalization has advantages. Most discussions of Kuhn’s theory are based on ambiguous mental models, and Kuhn’s work itself is textual, rich with ambiguity, multiple meanings, and implicit assumptions. More importantly, Kuhn offers no calculus by which one can assess whether the dynamics he describes can be produced by the causal factors he postulates. Formalization helps to surface auxiliary assumptions so they can be debated and tested. Formalization is complementary to the work of historians, sociologists, and philosophers of science working to develop and test theories of scientific change. Kuhn’s theory is also one example of a broader class of theories of revolutionary change. The model may provide insights into how revolutionary upheavals occur in other domains such as the social sciences. Finally, the model applies nonlinear dynamics to sociological phenomena. Modern theories of nonlinear, far from equilibrium systems, though emerging in the physical sciences, have great potential to illuminate evolutionary behavior in social, economic, and other human systems. Here we apply these tools to the evolution of scientific knowledge. As will be seen, the dynamics exhibit self-organization and path dependence, two common modes of behavior in nonlinear dynamical systems.

A Theory of Paradigm Evolution and Succession

We assume familiarity with Kuhn’s work and the many interpretations and alternatives to it. An important concept in Kuhn’s theory is the lifecycle of a paradigm. Kuhn describes a sequence of four stages: emergence, normal science, crisis, and revolution (followed by the emergence of a new paradigm). The emergence phase is characterized by the absence of commonly accepted beliefs or standards governing scientific activity. Conflict among paradigm-candidates is thus rooted in incompatible metaphysical beliefs and logics of inquiry. As a theory attracts nearly every scientist in the field – thereby providing a dominant paradigm – normal science begins. Debate over fundamental assumptions dwindles, and, convinced their paradigm is the proper way to characterize reality, scientists proceed to apply it to nature’s puzzles. When clashes between theory and reality do occur, they are often resolved in favor of theory. While some anomalies may accumulate as a result of puzzle-solving activity they do not necessarily induce crisis; on the contrary, it is often
presumed that the anomalous observations are wrong, or the calculations erroneous, so that further puzzle-solving effort will resolve the anomaly, a point Kuhn illustrates by citing anomalies facing Newtonian mechanics involving the speed of sound, the moon’s perigee, and the precession of the orbit of Mercury.\textsuperscript{15}

Normal science continues until a crisis arises. A paradigm can enter crisis when enough unsolved puzzles are recognized as important anomalies, and after these anomalies have resisted solution long enough to persuade practitioners that the theory must, after all, be questioned. Kuhn argues that ‘One source of the crisis that confronted Copernicus was the mere length of time during which astronomers had wrestled unsuccessfully with the residual discrepancies in Ptolemy’s system.’\textsuperscript{16} As persistent anomalies accumulate, increasing numbers of scientists will devote their time to solving them rather than other puzzles, and some may propose radical solutions. A revolution occurs when a new paradigm based on such a solution is adopted, and science is reconstructed from new fundamentals. Obviously the timing, character, and context of each stage differ from case to case. For example, a dominant paradigm in crisis may quickly be replaced, or crisis may deepen for decades as new theories fail to sprout or flower. The key issue is the relative importance of intrinsic explanatory power – the ‘truth’ of a new theory – compared to the social, political and cultural context or even chance factors (the existence of an Einstein, Bohr or Keynes) in conditioning which paradigm candidates flourish and which perish.

**The Model**

We construct a multi-paradigm model in which the creation of new theories is stochastic and endogenous. The model consists of a representation of the structure and activities of each paradigm, including membership, recruitment and defection; scientific activity such as puzzle solving and anomaly recognition; and the flows of people and information which couple the different paradigms that exist at any given time.
The heart of the model is the identification of the metaphysical and epistemological facets of paradigms with metaphors, limited representations of reality that crack when strained, producing anomaly and crisis. Four properties of metaphor which are also properties of paradigms bear particular mention. First, metaphor is everywhere. Nelson Goodman argues that ‘metaphor permeates all discourse, ordinary and special, and we should have a hard time finding a purely literal paragraph anywhere’. C. M. Turbayne goes further, suggesting metaphor permeates our thought as well as our language. Similarly, Kuhn stresses the priority of paradigms, suspecting that ‘something like a paradigm is prerequisite to perception itself’. Second, metaphor involves a ‘transfer of schema’ from one area of experience to another. Consider the metaphor ‘the brain is a computer.’ The characteristics of a computer are transferred, via the metaphor, to our image of the brain. The metaphor works because the characteristics of computers are well known and carry a constellation of meanings and examples that illuminate certain characteristics of the brain. For Kuhn paradigms operate similarly: scientists are taught to transfer familiar models to new puzzles, to ‘grasp the analogy’. Third, metaphors filter reality. Because metaphors are inevitably inexact, as are all models, they highlight certain relationships and suppress others. Metaphors focus our attention on particular facts and relations while others are pushed into the background. The filtering power of paradigms is central to Kuhn’s theory as well: ‘In the absence of a paradigm...all the facts that could possible pertain to the development of a given science are likely to seem equally relevant’. Finally, metaphors define reality. Max Black notes that ‘[i]t would be more illuminating in some of these cases to say that the metaphor creates the similarity than to say that it formulates some similarity already existing’. Kuhn attributes the same power to paradigms:

Yet metaphors are imperfect models. They are inherently limited, and if pushed too hard strain and crack. As a simple illustration, consider the metaphor ‘humans are wolves.’ Applying this
metaphor might generate insights, such as ‘humans engage in constant struggle,’ or ‘humans travel in packs.’ Eventually, however, overextension of the metaphor yields statements such as ‘humans have fur and walk on four legs,’ an assertion clearly at odds with our experience. The accumulation of these anomalous claims undermines the appeal of a metaphor, and can send it to its grave, disgraced as falsehood. Kuhn views the lifecycle of paradigms in a similar way. The elaboration and extension of a paradigm to new domains can lead to the accumulation of anomalies. As an ‘almost entirely typical’ example Kuhn cites the accumulation of anomalies in Newtonian mechanics, such as the repeated failure to detect drift through the ether resulting from the effort to provide a Newtonian foundation for Maxwell’s theory of electromagnetic radiation. As a result, ‘Maxwell’s theory, despite its Newtonian origin, ultimately produced a crisis for the paradigm from which it had sprung.’

Thus the central dynamic hypothesis of the model draws on the notion that paradigms are extended metaphors, and that metaphors are not unlimited in their applicability to reality. Specifically, we assume that the average difficulty of the puzzles faced by the practitioners of a paradigm increases as the cumulative number of puzzles they have solved grows. This ‘paradigm depletion’ represents the idea that each paradigm is a limited model of reality that may apply well in the domain of phenomena it was originally formulated to explain, but will be harder and harder to apply as scientists extend it to new domains. The formalization of this hypothesis is described below.

The model creates a simulated ecology of interacting paradigms, each representing a community of practitioners; recruitment and defection from that community; and the intellectual activities of the members such as formulating and solving puzzles, recognizing and trying to reconcile anomalies, and conceiving new theories. The model simulates the attitudes and beliefs of the practitioners within each paradigm through constructs such as ‘confidence in the paradigm’ and the time required to perceive unexplained phenomena as anomalies which challenge the theory. The major sectors of the model and the linkages among paradigms are shown in figure 1; we will use causal diagrams to
illustrate the feedback processes and stock-and-flow structure of the model. Each paradigm has the same internal structure; for clarity we display only the ‘ith’ and ‘jth’ paradigms.

**Confidence in the paradigm:** The focal point of the model is a construct called ‘confidence.’ Confidence captures the basic beliefs of practitioners regarding the epistemological status of their paradigm – is it seen as a provisional model or revealed truth? Encompassing logical, cultural, and emotional factors, confidence influences how anomalies are perceived, how practitioners allocate research effort, and recruitment to and defection from the paradigm. It is defined from 0 (absolute conviction the paradigm is false, nonsensical) through .5 (maximum uncertainty as to its truth) to 1 (absolute conviction the paradigm is truth). Pressures leading confidence to change arise both from within a paradigm and from comparisons with other paradigms (figure 2). Confidence rises when puzzle-solving progress is high and when anomalies are low. The impact of anomalies and progress is mediated by the level of confidence itself. Extreme levels of confidence hinder rapid changes in confidence because practitioners, utterly committed, dismiss any evidence contrary to their beliefs. Practitioners with only lukewarm commitment, lacking firm reasons to accept or reject the paradigm, are far more likely to alter their beliefs in the face of anomalies.

The external factors affecting confidence encompass the way in which practitioners in one paradigm view the accomplishments and claims of other paradigms against which they may be competing. We distinguish between the dominant paradigm, defined as that paradigm which has set the norms of inquiry and commands the allegiance of the most practitioners, and alternative paradigms, the upstart contenders. Confidence in a competing paradigm tends to increase if its anomalies are less than those of the dominant paradigm, or if it has greater explanatory power, as measured by cumulative solved puzzles. Confidence tends to decrease if the dominant paradigm has fewer anomalies or more solved puzzles. Practitioners in alternative paradigms assess their paradigms against one another as well as against the dominant paradigm. Confidence in an alternative paradigm tends to decrease (increase) if it has more (fewer) anomalies or fewer (more) solved puzzles than the most successful of its competitors.
**Puzzle Solving:** The determinants of puzzle solving, the heart of normal science, are shown in figure 3. Three categories of puzzles are distinguished. Solved puzzles are puzzles that have already been integrated into the corpus of theory and data that comprise the paradigm. Anomalies are unsolved puzzles that have been recognized as serious challenges to the theory. The third category, puzzles under attack, consists of those puzzles that have been formulated and are actively under study, but which have neither been solved nor yet recognized as anomalies. Four flows connect the different categories. Under normal conditions a puzzle, once formulated and attacked, will be solved, adding to the cumulative stockpile of knowledge generated by the paradigm. Such puzzles flow into the class of solved puzzles via the puzzle-solving rate. But as the intrinsic difficulty of puzzles grows, a growing number will resist solution long enough to be recognized as anomalies. Anomalies may sometimes be resolved, adding to the stock of solved puzzles via the anomaly resolution rate. The shifting balance between these flows determines the behavior of the system.

**Puzzle formulation and puzzle solving rates:** The rate at which scientists formulate and solve puzzles depends on the number of puzzles under study, the fraction of practitioners involved in puzzle-solving, the fraction of their time devoted to puzzle-solving, and the average difficulty of the puzzles (figure 4).

The average difficulty of the puzzles currently under attack depends on how far the root metaphor defining the paradigm has been extended. As described above, the average difficulty of puzzles is assumed to rise as the paradigm is applied to more phenomena, phenomena increasingly removed from the original domain for which the paradigm was formulated. Specifically, the average difficulty of new puzzles to be solved, \( D \), rises as the number of puzzles the paradigm has solved grows. We assume

\[
D = \left( \frac{SP}{C} \right)^\gamma
\]  

(1)

where \( SP \) is the cumulative number of solved puzzles. The nominal solved puzzle reference, \( C \), determines the intrinsic capability of each paradigm, and \( \gamma \) is the rate at which difficulty rises with cumulative progress. The exponent \( \gamma \) controls the rate at which difficulty grows. When \( \gamma < 1 \), the
rate at which puzzle difficulty rises with cumulative progress becomes progressively smaller, while \( \gamma > 1 \) indicates the difficulty of puzzles on the margin rises ever faster. For parsimony we assume \( \gamma = 1 \). Small values of the reference capability \( C \) mean a paradigm’s intrinsic explanatory power is low – the difficulty of new puzzles rises rapidly as normal science proceeds. Large values indicate a more powerful paradigm, one that could encompass a wider array of phenomena. Intrinsic capability is determined by a host of factors including the richness of the theoretical constructs emerging from the paradigm’s root metaphor and of course the particular genius of the paradigm’s creators.\(^{27}\)

As the difficulty of puzzles grows, puzzle-solving may slow and more unsolved puzzles may become recognized as anomalies. If the stock of anomalies grows too large, the confidence practitioners have in the ‘truth’ or utility of the paradigm may fall. The collapse of confidence is self-reinforcing: anomalies erode confidence, and falling confidence increases the ability and willingness of practitioners to perceive the gaps in the theory.

The majority of practitioners will usually be involved in puzzle-solving, while some will be working to resolve anomalies, and others try to generate alternatives or engage in other work such as administration or popularization. The distribution of practitioner effort among these three categories is a function of confidence in the paradigm. The higher the confidence, the greater the fraction of practitioners involved in normal science and anomaly resolution. As confidence falls, a larger fraction of practitioners turn their attention away from the normal science they increasingly come to doubt.

*Anomaly recognition rate: Anomaly recognition is a subtle psychological process.*\(^{28}\) Kuhn notes that anomalies are not simply experiments that run counter to expectation as there are always disagreements between data and theory. Rather, a puzzle becomes recognized as an anomaly when normal science repeatedly fails to resolve the differences. A proxy for this process is the length of time an unsolved puzzle has resisted resolution. Following Kuhn, we assume that the longer an unsolved puzzle has resisted solution, the greater the probability it will be recognized as an
anomaly. Thus, the probability a puzzle is recognized as an anomaly rises as the average difficulty of puzzles rises. However, recognition of anomalies also depends on the degree to which practitioners are conditioned to see reality as consistent with their paradigm. Kuhn cites the Bruner-Postman playing card experiments to illustrate the concept of a paradigm conditioning perceptions, concluding ‘In science, as in the playing card experiment, novelty emerges only with difficulty, manifested by resistance, against a background provided by expectation.’ Thus in the model the average time required to recognize an unsolved puzzle as an anomaly depends on practitioners’ level of confidence in the paradigm. High levels of confidence slow the recognition of anomalies as practitioners’ expectations, behaviors, and even perceptions become increasingly conditioned to be consistent with the paradigm. Decreases in confidence will cause more of the puzzles under attack to be considered anomalous as practitioners’ skepticism and doubts grow.

Anomaly resolution rate: The rate at which anomalies are resolved depends on the number of practitioners in sanctioned research, the fraction of those involved in anomaly resolution, and the average difficulty of anomalies (figure 5). Anomalies are assumed to be more difficult to solve than puzzles, and as the difficulty of puzzles increases, the difficulty of anomalies rises as well. The fraction of practitioners involved in anomaly resolution depends on the balance between the number of anomalies and the acceptable number. The acceptable number of anomalies is the number that can be tolerated without losing confidence in the paradigm. If the number of anomalies increases, additional practitioners are drawn into anomaly resolution in an attempt to solve the major outstanding problems challenging the theory. This negative feedback is comparatively weak, however: Kuhn argues that most practitioners are reluctant to work on anomalies, preferring instead the relative safety and professional rewards of puzzle-solving. The belief that anomaly hunting may be hazardous to your career is widespread among scientists today and often reinforced in the professional journals. Examples abound: a recent news article in *Science* reports that the Nobel laureate physicist Martin Perl is currently running experiments designed to detect the fractional electric charge which would indicate the existence of free quarks, a phenomenon counter to the predictions of quantum chromodynamics, the long-successful theory of the strong force pioneered
by Murray Gell-Mann and George Zweig in the 1960s. Though Perl asserts ‘a positive finding would overturn 30 years of our thinking about strong interactions’, he ‘as a tenured Nobel laureate, has the ‘luxury’ of continuing the search’, while others caution that ‘a younger scientist trying to make a reputation would be well-advised to avoid this line of work.’

**Practitioner Population:** The population of practitioners committed to each paradigm is endogenous, increasing with recruitment and decreasing with retirement of elder scientists and defection of others to competing paradigms. Without loss of generality we assume the total population of scientists is constant: scientists who leave one paradigm enter another; and entry of young scientists is balanced by retirement of the old. The assumption of constant total population simplifies the interpretation of the results but is in no way essential to the main conclusions. Practitioners defect based on their confidence relative to the confidence of those in the dominant paradigm (figure 6). The greater the (negative) discrepancy between a challenger’s confidence and confidence in the dominant paradigm, the larger the proportion of the challenger’s practitioners will defect. Recruitment is proportional to a paradigm’s relative attractiveness and its total number of practitioners. The greater a paradigm’s attractiveness, the greater the proportion of defectors from other paradigms it will recruit. Attractiveness is proportional to the number of practitioners since large paradigms are assumed to get more funding, train more students, and have a larger voice in tenure and other peer-career decisions than small paradigms. Attractiveness also depends on the confidence of the paradigm’s practitioners. Here confidence captures the excitement and enthusiasm flowing from a successful endeavor.

**The Creation of New Paradigms:** We model the creation of a new paradigm as a stochastic event whose probability depends upon the distribution of practitioner activities in the currently dominant paradigm. Practitioners may toil in normal science (puzzle-solving), anomaly resolution (the attempt to reconcile anomalies with the current paradigm), and other activities (described by Kuhn as including philosophical reconsideration of the paradigm and other activities not sanctioned by the dominant paradigm). In general, each of these activities may result in the creation of a new
paradigm, but the probability that a new paradigm is created as a result of a practitioner year of effort devoted to each activity may differ. Thus:

$$PA_t = p_{ps} \cdot PPS_t + p_{ar} \cdot PAR_t + p_{oa} \cdot POA_t$$  \hspace{1cm} (2)

where

- $PA$ = probability a new paradigm is created (per year);
- $PPS$ = practitioners in the dominant paradigm engaged in puzzle-solving (practitioners);
- $PAR$ = practitioners in the dominant paradigm engaged in anomaly resolution (practitioners);
- $POA$ = practitioners in the dominant paradigm engaged in other activities (practitioners);
- $p_{ps}$ = probability of creating a new paradigm per practitioner year of effort in puzzle-solving;
- $p_{ar}$ = probability of creating a new paradigm per practitioner year of effort in anomaly resolution;
- $p_{oa}$ = probability of creating a new paradigm per practitioner year of effort in other activities.

Following Kuhn, we assume that normal science is unlikely to produce new paradigms, focused as it is on solving puzzles within the context of the existing paradigm. Other activities are more likely to produce a new paradigm, while effort devoted to anomaly resolution is most likely to result in the creation of radical new theories. Thus $p_{ar} > p_{oa} > p_{ps}$ (the values of these parameters are small enough that the overall probability of creating a new paradigm in any given year is low). In the model, the distribution of effort among these three activities is endogenous. Thus the probability that a new paradigm will be created in any time period is endogenous and will vary as practitioner effort changes in response to the changing health of the dominant paradigm. Once a new paradigm is launched, we assume it begins with a small number of practitioners (five), a confidence level of .5 (neutral), a very small stock of solved puzzles and no initial anomalies. The newly launched paradigm must then compete against other existing paradigms and will succeed or fail to the extent it can solve puzzles and resolve anomalies such that confidence in that paradigm grows. During a period of crisis the probability of creating a new paradigm may rise and remain high long enough for more than one new paradigm to be launched. In this case the newly created paradigms will vie for ascendancy not only against the dominant paradigm but against one another.
Exploring the Dynamics of Paradigm Development

We begin by simulating the model with fully endogenous competition among paradigms. The initially dominant theory (paradigm 1) is initialized in the midst of normal science, and new theories are created stochastically, with a probability depending upon the vitality of the dominant paradigm as specified by eq. 2. We allow the intrinsic puzzle-solving capability of each paradigm to differ. Specifically, the rate at which puzzle-solving becomes difficult as solved puzzles accumulate (the paradigm’s inherent potential, C) is chosen randomly from a lognormal distribution (truncated such that \( C \leq 800 \)). Otherwise all paradigms have identical structure and parameters.

Figures 7a and 7b show the first 1400 years of a representative simulation. The simulation yields a succession of dominant paradigms in which the initial paradigm gives way to challengers, each of which go through the typical lifecycle as described by Kuhn, though with variations in length and timing. What is most interesting is not what the figures display but what they conceal. Not all new theories succeed. As evident in figure 7a, paradigms 2-4, 7, 9-12, 15, 17-18 never become dominant (11 out of 19, or nearly three-fifths). Many new theories face early extinction. These figures illustrate what Kuhn calls the invisibility of revolutions, where the linear and cumulative character of normal science portrayed in the textbooks conceals the contentious character of actual scientific practice. 31 The simulation replicates the ‘punctuated equilibrium’ pattern described by Kuhn, and observed in many other fields. 32

The endogenous forces underlying a paradigm’s evolution are best illustrated by focusing on the lifecycle of a particular paradigm. Figure 8 enlarges that portion of figure 7a portraying the lifecycle of paradigm 14. Around year 500 paradigm 8 is in the full flower of normal science, with 100% of the practitioners, a high level of confidence, and few anomalies. Paradigm candidates 9-12 are, by chance, created during the period of normal science and quickly perish. However, the very success of the theory leads practitioners to apply it to more and more phenomena. Anomalies slowly accumulate as puzzles gradually become more difficult to solve, eventually leading to crisis and a drop in confidence. Paradigms 13 and 14 are both launched during the crisis of paradigm 8 (around
years 545 and 566, respectively). By chance, paradigm 13 has a very low inherent potential. Its rapid rise around year 580 is matched by an equally rapid drop as its practitioners quickly exhaust the limited potential of its underlying metaphor. Paradigm 14 benefits from the early demise of paradigm 13. Figure 9 illustrates the details of paradigm 14’s lifecycle. In the early period (years 566 to 610), confidence rises dramatically, since initial puzzle-solving progress is rapid and anomalies are low. The paradigm, initially untested, proves itself capable of solving puzzles, and thus attracts more practitioners, further boosting confidence. The rise of the theory is self-reinforcing through multiple positive feedback processes (figure 10): rising confidence, faster recruitment and successful puzzle-solving boost practitioner confidence, leading to more focused and successful effort, articulation and improvement of theory and technique, and still greater success in puzzle solving, further boosting confidence and attracting still more members. Rising confidence and familiarity with the paradigm increasingly condition the perceptions and expectations of practitioners, suppressing the recognition of anomalies; a low level of anomalies further increases practitioners’ confidence in and commitment to the theory. These and other positive feedbacks (shown in figure 10) bootstrap paradigm 14 into dominance by around year 625, its metaphor, method and metaphysics triumphant over the now-discredited paradigm 13.

Normal science, a period of high productivity in which practitioners engage primarily in puzzle-solving and are blinded to potential anomalies by their faith in the paradigm, occurs for paradigm 14 approximately between years 620 and 830. During the successful period of normal science practitioners focus their efforts on puzzle solving and the probability a new paradigm is created falls (see eq. 2). In this fashion, success suppresses the generation of new competitors which might challenge the dominant paradigm, leading to further success. Through this self-reinforcing feedback a successful theory alters its own environment in ways that provide further advantage. This important dynamic operates through the training of graduate students, which reproduces the worldview and prejudices of the dominant theory and socializes them in the accepted literature; through the control of institutions via appointments and tenure; through resource allocation via peer review of grant proposals; and through access to journals via control of editorial boards and the
selection of referees. However, occasionally a new theory does emerge during periods of normal science, such as paradigm 15 just before year 750 (figure 8). Such challengers usually perish in the face of competition with the still successful dominant paradigm. Indeed, paradigm 15 disappears within a few years.

As paradigm 14 is elaborated and extended, puzzles slowly become more difficult to solve and anomalies begin to accumulate. Although the fraction of all practitioners committed to the paradigm remains high throughout the period, confidence begins to fall slowly around year 780, as does the fraction of practitioners engaged in sanctioned research (puzzle-solving). By year 850 the paradigm is in crisis due to high anomalies and slowing progress. The positive feedbacks which had previously caused membership to rise now cause accelerating collapse. The progress of normal science has increased the difficulty of puzzles, since practitioners have begun to apply the paradigm beyond the scope of its root metaphor. As anomalies increase, a few practitioners leave puzzle-solving, eroding progress and decreasing confidence further. Practitioners, increasingly sensitive to the paradigm’s limitations, become more apt to see difficult puzzles as anomalies, thus further increasing anomalies and decreasing confidence.

As the number of practitioners engaged in normal science falls and those in anomaly resolution and other activities increase, the probability that a new paradigm will be created gradually grows. Around year 855 a new paradigm is in fact created (paradigm 16 in figure 8). Since the new theory emerges during the crisis of paradigm 14, it quickly gains adherents while paradigm 14 loses members. Confidence and membership in paradigm 16 then accelerate sharply through the same positive feedbacks that led to the growth of paradigm 14. The cycle is completed as paradigm 14’s confidence and membership eventually fall to 0 while 16 grows to dominate the field. What was once uncontested Truth is now seen as primitive error. Paradigm 17, created around year 870, is quickly crushed by the now successful 16.

The many positive feedbacks described above and illustrated in figure 10 create the self-organizing dynamic by which uncommitted and unorganized practitioners coalesce into a highly focused
paradigm with a productive normal science. Through these feedbacks a successful paradigm alters its environment by suppressing the creation of competitors and rapidly starving any that do emerge of the resources they would need to succeed. The same feedback processes operate in the opposite direction during the crisis period to accelerate the collapse of a paradigm which has accumulated sufficient anomalies for confidence to begin falling.

The simulations raise a number of important questions. Why do some paradigms rise to dominance while others quickly wither? Does the fate of a new paradigm depend on its intrinsic capability to explain nature or on situational contingencies surrounding its birth? Does ‘truth’ eventually triumph as better theories defeat inferior ones, or is timing everything?

There is evidence for both positions in the results. Supporting the view that intrinsic explanatory power is critical are examples such as paradigm candidate 13, which rapidly exhausts its low intrinsic potential and never achieves dominance. However, intrinsic capability does not explain the fate of many others. Consider paradigms 8 and 9 in figures 7a and 7b, launched around years 199 and 203, respectively. Although they emerge only about 4 years apart, during the crisis of paradigm 5, paradigm 8 comes to dominate the field, while paradigm 9 eventually perishes. Here the contingency of outcomes on situational factors is decisive. Paradigm 8 does not succeed because of a head start in attracting practitioners: between years 212 and 215 it actually has the same number as paradigm 9. Nor is paradigm 8’s success a result of superior explanatory power: by chance, paradigm 9 is endowed with a potential 13% greater than paradigm 8. The difference in their destinies lies in their levels of confidence. In the year 212 paradigm 8, though equal in size to paradigm 9, is slightly more attractive to adherents of crisis-ridden paradigm 5 because its adherents, having had a 4 year lead over paradigm 9 in solving puzzles, have been able to articulate their paradigm more coherently and persuasively than their chief rivals. The small advantage held by paradigm 8 is amplified as success begets success through the many positive loops surrounding the emergence process (figure 10). Paradigm 8 eventually dominates science, while paradigm 9 slowly fades into obscurity, to be remembered, if at all, as a blind alley, foolish error, or curiosity.
The simulation illustrates the subtle interplay between endogenous feedback processes and contextual, situational factors in determining the dynamics and succession of paradigms. The basic life cycle of paradigms is determined by the recursive, reflexive feedback loop structure discussed above. Figure 11 shows some of the positive feedback loops that act to differentiate competing paradigms (the many negative feedbacks are not shown). These positive feedbacks boost confidence and rapidly generate a focused community from a promising but unexplored new idea. They give a paradigm with an initial advantage an edge in recruitment of new members, leading to still greater advantage. Consider paradigm $i$ in figure 11. If the number of anomalies and solved puzzles in paradigm $i$ compare favorably with the accomplishments of competitor paradigms, the confidence of practitioners in $i$ will rise and the confidence of those in its competitors will fall. The attractiveness of $i$ relative to others grows, thus strengthening $i$ and weakening its competitors. The net flow of practitioners into paradigm $i$ will increase the gap in solved puzzles between $i$ and its competitors, causing the gap in confidence to widen still further. The self-reinforcing differentiation continues until one paradigm emerges dominant. These same loops are responsible for the resistance of the dominant paradigms to challenges, as high confidence suppresses the creation and retards the progress of new theories. High confidence leads to normal science and low anomalies, suppressing the type of inquiry likely to lead to the creation of new paradigms (eq. 2). And should by chance a new theory be created, the high confidence and low anomalies of a dominant paradigm make it unlikely a new theory can succeed, even if it has high intrinsic explanatory potential. Note that once a dominant paradigm begins to experience depletion of its root metaphor these same loops accelerate the collapse.

In the early phase of a competition between two or more paradigm candidates, when the differences among the competing theories are small, chance events can perturb the system sufficiently to shift the advantage to a previously weaker rival. Such random events might include factors related to the theory such as the announcement of an important experimental result, but can also include events wholly outside of science such as the illness of the candidate’s champion or political upheavals which disrupt the work of key people. However, as the positive loops confer greater and greater
advantage to one of the contending theories, the likelihood that particular events can overcome the advantage of the leader rapidly diminishes, until the system has effectively ‘locked in’ to a solution. Once such lock-in has occurred, the dominance of the winning theory is assured (until its own crisis). Yet which particular theory becomes dominant can be a matter of chance events and perturbations early in the emergence phase.

The prevalence of positive feedback processes in the dynamics means that historical contingencies attending the creation and early years of a new theory strongly condition their fate. While it is obvious that the creation of a new theory is intrinsically unpredictable, the simulation shows clearly that, once created, the likelihood any given new paradigm grows to dominance is strongly contingent on the environment into which it is launched – an environment that in turn depends on the history of the paradigms preceding it. The prevalence of positive feedback processes in paradigm development means that the evolution of the system as a whole is strongly path-dependent.

The ability of positive feedback processes to create path-dependent lock-in to particular equilibria from an initially undifferentiated choice set has been amply documented in biological, economic, technological, and other systems. Examples include the universal left-handed chirality of DNA throughout the plant and animal kingdom, the choice of technological standards such as the gauge for a railroad, the designation of Greenwich as the prime meridian for longitude, the length of the standard meter in Paris (or the choice of the metric over the English system), or the dominance of the IBM/Microsoft Windows architecture for personal computers. Even when all choices are equally attractive ex ante, the symmetry is broken by microscopic noise or other perturbations. The positive feedbacks then amplify these small initial differences to macroscopic significance, and, once a dominant design has emerged, the costs of switching become prohibitive, so the equilibrium is self-maintaining (at least until there is an architectural shift that renders the dominant design obsolete, as in the pending replacement of current broadcast television standards by HDTV).
To test the argument above and quantify the roles of intrinsic versus contingent factors, we analyzed the pooled results of fifty-seven 2000-year model runs. The only parameters varied were the paradigm’s intrinsic explanatory power and the random number seed affecting the launch of new paradigms. In order to eliminate initial transients and end effects the first and last five paradigms of each simulation are eliminated from the analysis. There are 350 dominant paradigms and 676 never-dominant paradigms in the sample. Most of the runs were made with randomly selected intrinsic capability, C. In some runs all paradigms had identical intrinsic capabilities, with C=200, 300 or 400.

We consider a LOGIT model with three explanatory variables: intrinsic capability (C), the confidence in the dominant paradigm at the time the new paradigm is launched (CP_{dom}), and the number of competitor paradigms (not including the dominant paradigm) each new paradigm faces when launched (Table 1). Since the probability of success need not depend linearly on the number of competitors, we treat the number of competitors as a categorical variable, constructing dummy variables for situations of 1, 2, 3 and 4 competitors. Thus, COMPET_i=1 if the number of competitors equals i at the time each paradigm is founded, and zero otherwise:

\[
P_t(Dom) = \frac{1}{1 + \exp(-(b_0 + b_1 C + b_2 CP_{dom} + \sum_{i=1}^{4} w_i COMPET_i))}
\]  

where the subscript t indicates that the probability is calculated in the year each new paradigm is created.

Table 2 shows how well the model predicts actual successes and failures, where an estimated probability greater than .5 is interpreted as a prediction that the paradigm becomes dominant and estimated probabilities < .5 are interpreted as predictions of failure. Overall, 83% of the cases are predicted correctly. The sensitivity and specificity of the model are roughly equal (both ≥ .83), indicating the model’s error rate is about the same for type I and type II errors (predictions of dominance when the paradigm in fact fails versus predictions of failure when the paradigm in fact succeeds). The statistic \( \lambda_b = 1 - ((\text{errors|model})/(\text{errors|no model})) \) measures how much the model improves prediction success compared to the chance success rate. In the absence of the model the
best guess is that any paradigm picked at random is that it fails, since fully 66% of the paradigms in the sample never become dominant. The model reduces the error rate by half compared to chance.

The regression results (table 1) show that all estimated coefficients have the predicted signs. A new paradigm’s chances of success rise with greater intrinsic capability, a weaker dominant paradigm, and a smaller number of competitors. However, the effect of a paradigm’s intrinsic explanatory potential, C, on its probability of success is not significant, while the contextual variables are highly significant. The values of the individual coefficients illustrate the weak role of intrinsic capability in comparison to the contextual factors in determining whether a paradigm becomes dominant. The maximum value C can take is 800, so its maximum input into the LOGIT equation is (.000686)(800)=0.55. The value CPdom would have to take to offset the impact of C = 0.55 is 0.55/7.27 = .08. Thus whenever CPdom>0.08, its contribution to a new paradigm’s probability of success exceeds the greatest contribution C could ever make. Given that more than 90% of all paradigms are created when CPdom≥0.10, the influence of the dominant paradigm on the fate of the upstart nearly always outweighs that of the new paradigm’s intrinsic capability.

The relative importance of intrinsic capability C versus the contextual factors CPdom and the number of competitors COMPETi is illustrated in figure 12. Each point in the plot represents the probability of dominance of a particular paradigm, as predicted by its intrinsic capability, the number of competitors it faces at birth (excluding the dominant paradigm), and the confidence of the dominant paradigm it faces. The smooth curves plot the predicted probability of dominance as CPdom varies over the [0,1] interval, for each number of competitors and assuming intrinsic capability takes on its mean value Cavg = 371.4; that is:

\[
P_t(\text{Dom}) = \frac{1}{1 + \exp(-(5.44 + .000686C_{\text{avg}} - 7.27C_{\text{dom}} + w_i))}. \tag{4}
\]

For new paradigms competing only against the dominant paradigm, the probability of dominance is given by the curve in the upper-right. Curves are also displayed for environments with two and three competitors. The curve for four competitors has probabilities ≈ 0. For all but the smallest
values of $C_P^{\text{dom}}$, the greater the number of competitors, the less likely a new paradigm becomes dominant. Likewise, the greater the value of $C_P^{\text{dom}}$, the less likely a new paradigm is to become dominant. The regression results and figure 12 show the number of competitors existing at the time a new paradigm is created strongly influences its fate. Latecomers are not likely to succeed. When $C_P^{\text{dom}}$ is between about 0.1 and 0.6 a new paradigm stands a better than even chance of becoming dominant if it faces a total of two competitors or less, and will likely fail if there are three or more competitors. When $C_P^{\text{dom}}$ is between about 0.6 and 0.8 the new paradigm is more likely than not to become dominant if it faces only the dominant paradigm, likely to fail if it faces two competitors, and almost sure to die if faces three or more competitors.

Figure 12 also underscores the weak role of intrinsic factors in determining a paradigm’s probability of dominance. The data fall very close to the predicted values. Departures from these curves represent the effect of the variations in intrinsic capability on the likelihood of dominance. Capability has an effect approaching that of the number of competitors only when $C_P^{\text{dom}}$ is very low or very high, and in all cases the overall magnitude is quite small.

Thus the likelihood a new paradigm rises to dominance in the model is overwhelmingly determined by historical contingencies and only weakly influenced by its intrinsic explanatory power. The relative importance of inherently unpredictable situational factors is not particularly sensitive to the parameters. Rather it is a consequence of the many positive feedbacks by which paradigms bootstrap themselves from doubt to normal science (figure 10).

Thus contextual factors predominate in determining the likelihood a given new theory will become successful, while intrinsic capability has only small effect. But how do internal and contextual factors interact to determine how long those paradigms that do become successful dominate their field? Do intrinsically powerful paradigms remain dominant longer than their weaker counterparts? Here one would expect that the paradigms with greater explanatory power should remain dominant longer. Figure 13 shows a paradigm’s duration of domination as a function of its intrinsic
capability. Few paradigms with intrinsic capabilities less than 100 ever become dominant. Those with higher capabilities that do rise to dominance fall along two distinct lines, or modes of behavior. Mode 1 shows what one would expect: the greater the intrinsic capability, the longer the period of normal science. Within mode 1 there is a roughly linear dependence of the duration of normal science on intrinsic capability, with the duration of normal science increasing by about 50 years for every 100 unit increase in intrinsic capability. This is expected given the assumed linear relation between cumulative accomplishment and the difficulty of new puzzles on the margin (the assumption $\gamma = 1$ in eq. 1). However, a second cluster of successful paradigms, denoted mode 2, experience much shorter periods of dominance. For these theories, greater explanatory power has but little effect on longevity. Paradigms in mode 1 can remain dominant two to five times longer than paradigms in mode 2 with identical intrinsic explanatory potential. The differences in outcomes arise from differences in the circumstances attending the birth of these successful theories. The paradigms in mode 1 generally emerge when confidence in the dominant paradigm is relatively high (typically exceeding 0.8). Most scientists are still satisfied with the dominant paradigm, so the rate of defections to the new paradigm is relatively slow. During this time, however, the few adherents of the new paradigm are able to solidify the foundations of their theory. Anomalies grow very slowly as increasingly confident practitioners solve the relatively easy puzzles for which their paradigm is well suited. Their confidence rises. By the time the crisis of the dominant paradigm deepens and its members become disaffected, the initial adherents of the new theory will have articulated it well enough to provide an attractive and viable alternative. With high confidence to focus research on the puzzle solving of normal science the new paradigm is poised to realize its intrinsic potential.

The paradigms in mode 2, however, generally emerge when confidence in the dominant paradigm is already quite low (usually $< 0.4$), indicating a field experiencing a prolonged crisis during which no satisfactory alternatives have arisen. Thus, as uncertain as the new paradigm is, it nonetheless quickly wins new members. The rapid influx of new practitioners means the rate of effort is high. The underlying metaphor defining the paradigm will be extended rapidly into new terrain, and the
average difficulty of puzzles rises rapidly, increasing the number of puzzles likely to be seen as anomalies. Most important, the influx of new practitioners occurs when confidence is low, meaning basic disagreements about methods, data, and criteria for validity still persist. Without the acculturation and perceptual filters provided by a well-articulated paradigm, disagreements and anomalies arise at an alarming rate. Practitioners quickly begin doubting the new paradigm, and confidence can fall. Falling confidence causes people to perceive anomalies still more readily, further decreasing confidence. The new paradigm rapidly disintegrates, its high intrinsic potential largely unrealized. While intrinsic potential is strongly related to longevity for those paradigms that succeed, contextual factors even here are critical.

The dynamics here resemble the life cycle of intellectual fads, in which a promising new idea rapidly becomes fashionable, but through excessive optimism, aggressive ‘marketing’ or popularization, rapid influx of poorly trained practitioners, or lack of established protocols and successes, expectations outrun achievements, leading to a backlash and disaffection. Such fads are commonplace, especially in (quack) medicine and most particularly in the world of management theory, where ‘new paradigms’ are routinely touted in the pages of popular and academic journals of management, only to be replaced in the next issue by what many business people have cynically come to call the next ‘flavor of the month’. No doubt many such fads have no intrinsic merit (in our terms, intrinsic capability \( C \) is low) so their rapid demise is the desired and rational outcome (similar to the fate of the low potential paradigm 13 in figure 8). However, the rise and fall of these fads in the business world occurs far more rapidly than the follow up and assessment research which could test whether the ideas and methods of each new theory actually work. In such cases, the baby will sometimes be thrown out with the bath water (in our terms, theories with high intrinsic capability can be abandoned too soon). In the sciences, so-called ‘chaos theory’ or ‘complexity theory’ provides a recent example. Successful popularization and ill-advised claims by advocates for the universality and utility of ‘complexity’ as a ‘new paradigm’ for the reconstruction of disciplines as disparate as physics, biology, and economics have led to a recent backlash.
Conclusion
Before turning to the conclusions, we pause to consider the limitations of the model and of formal modeling. All models (formal or otherwise) are inevitably less than the world their authors seek to portray. We therefore agree with Nancy Cartwright that models ‘are a work of fiction’. Of course the model is not comprehensive, nor does it capture all the subtleties of Kuhn’s theory. Rather, we seek to demonstrate that it is both desirable and possible to portray in a formal model the causal hypotheses embodied in written theories of scientific endeavor and test whether they can generate the dynamics as those authors see them. The process of formalizing such hypotheses helps to identify inconsistencies, implicit assumptions, glosses and errors in the mental simulations authors necessarily perform to infer the dynamics of science from their theories of its structure. Such an endeavor is worthwhile as a complement to historical and sociological studies. Complete documentation of the model is available; we invite others to replicate, critique, revise, and extend the model to test views of scientific development different from ours.

The simulation results suggest an important role for situational contingencies in the evolution of science. We find that the fate of a particular new theory or paradigm is strongly conditioned by the circumstances surrounding its creation, and only weakly influenced by its explanatory power or logical force (at least for theories above a minimum threshold of explanatory power). Environmental conditions at the time a new theory is created such as the morale and confidence of practitioners in the old paradigm and the number of contending alternative new theories powerfully determine whether a new theory will rise to dominance or quickly perish. In particular, the simulations show new theories with great explanatory power frequently fail to attract a critical mass of adherents, while weaker ones often triumph. The occasional eclipse of the strong by the weak is not a pathological outcome, but rather a normal part of scientific activity as we have modeled it.

The interplay between intrinsic explanatory potential and historical contingency is quite subtle. A paradigm’s inherent potential – its logical force and power to explain nature – does influence its future development: of those paradigms that manage to survive their initial years, those that are
more powerful remain dominant longer, on average, than those that are weaker. But the impact of intrinsic capability on the duration of dominance for any given paradigm is mediated by the competitive conditions in the emergence period. In particular, weak competitive environments make it more likely a new paradigm will rise to dominance, but can condemn even powerful paradigms to early deaths as they are extended too far and too fast, generating anomalies and destroying confidence prematurely. On the other hand, though competition reduces the likelihood of survival, competition gives those that do survive time to bootstrap themselves into normal science, insulating them against mere disconfirmation, and ensuring they persist until the anomalies ultimately causing revolution, in Kuhn’s words, ‘penetrate existing knowledge to the core’.38

Most important, however, competition does not serve to weed out the weak paradigms so the strong may grow. On the contrary, competition decimates the strong and weak alike – we found that intrinsic capability has but a weak effect on survival. The hazard rate for paradigms seems to depend almost entirely on the environmental conditions surrounding their birth. This is a sobering result, since we can never know the micro-level contingencies of history that can prove decisive; here favoring an intrinsically weak paradigm, there killing an intrinsically strong theory.39 These characteristics of the competition among paradigms are consequences of the powerful positive feedback processes operating within and among paradigms. These positive loops can amplify microscopic perturbations in the environment – the local conditions of science, society, and self faced by the creators of a new theory – until they reach macroscopic significance. Such dynamics are the hallmark of self-organizing evolutionary systems.

Contemplating the reflexive feedbacks between people and the world, Kuhn, in 1990’s ‘The road since Structure’, captured the essence of path-dependence, arguing that ‘scientific development must be seen as a process driven from behind, not pulled from ahead – as evolution from, rather than evolution towards.’40 Yet while acknowledging the role of the biological, cognitive, and social in the evolution of science, Kuhn argues strongly that path-dependence does not mean the course of scientific development is entirely arbitrary or reality merely a social construction:
the world is not invented or constructed....[It] has been experientially given, in part to the
new inhabitants directly, and in part indirectly, by inheritance, embodying the experience of
their forebears. As such, it is entirely solid: not in the least respectful of an observer's
wishes and desires; quite capable of providing decisive evidence against invented hypotheses
which fail to match its behavior. Creatures born into it must take it as they find it. They can,
of course, interact with it, altering both it and themselves in the process, and the populated
world thus altered is the one that will be found in place by the generation which follows.”

Through these feedbacks the world we inhabit is made; it is a world in which, as Kuhn says, ‘small
changes...can have large-scale effects.”

2 Notably Paul Feyerabend, *Against Method*, (London: NLB, 1975), and famously, Ludwik Fleck, whose 1935 theory of the social construction of scientific facts was noted by Kuhn op. cit., vii, as ‘an essay that anticipates many of my own ideas’. Of course, Kuhn can be situated in a long tradition of philosophers, linguists, and psychologists who reacted against realist and positivistic views of science, perception, and knowledge.

3 Kuhn, op. cit., 208.


6 The model is based on Sterman’s (1985) model of Kuhn’s theory (John D. Sterman, ‘The Growth of Knowledge: Testing a Theory of Scientific Revolutions with a formal model’, *Technological Forecasting and Social Change* 28(2) (1985), 93-122), which portrayed how internal factors could produce the collective behavior Kuhn identified as characteristic of scientific development. Jason Wittenberg, ‘On the very idea of a system dynamics model of Kuhnian science’, *System Dynamics Review*. 8(1) (1992) 21-33) criticized this model for having excluded contextual and contingent elements such as the existence of competitor paradigms. In this paper we extend the original model to allow for explicit competition among different theories.


Kuhn’s work has led to literally hundreds of interpretive and critical analyses. Hoyningen-Huene 1993 op. cit. provides a critical assessment and the most recent survey and bibliography; see also Imre Lakatos and Alan Musgrave, *Criticism and the Growth of Knowledge*, (Cambridge: Cambridge University Press, 1970).

Kuhn 1970 op. cit. 13-15 illustrates with the state of electrical research before Franklin and his successors provided the field with a paradigm.

Kuhn op. cit., 81.

Kuhn op. cit., 82.


Kuhn op. cit., 113.
Goodman, op. cit., 71-80.

Kuhn op. cit., 189.

Kuhn op. cit., 15.


Kuhn op. cit., 111.

Kuhn op. cit., 74.

George Richardson and Alexander Pugh, *Introduction to System Dynamics Modeling with DYNAMO*, (Portland, OR: Productivity Press, 1981; see also Sterman 1985 op. cit. A documented listing of the computer program is available from the authors.

Masterman (1970 op cit.) viewed paradigms as analogous to nonrenewable resources, arguing that the domain of applicability for a paradigm was finite, so all attempts to extend it further would yield only anomaly, just as a mine shuts down after all its gold is extracted. Her assumption would mean that puzzle solving difficulty in the model would become infinite at some finite value of cumulative solved puzzles. We make the weaker assumption that the puzzle solving potential of paradigms is infinite, though it rises continuously on the margin as solved puzzles accumulate.

Lightman and Gingerich op. cit.

Kuhn op. cit., 62ff.


Kuhn op. cit., 136-143.

e.g. Gersick op. cit. and Tushman and Anderson op. cit.

See Arthur 1994 op cit. for economic examples and theory.
Note that there are more paradigms in the dataset with intrinsic capabilities of 200, 300, and 400 than there are with other capabilities. In several of the simulations we controlled for variations in puzzle solving potential to uncover the sources of variation in emergence. In the other simulations the intrinsic potential of each paradigm was drawn from a log-normal distribution truncated such that capability was ≤800. This limit in no way changes the model’s qualitative behavior.


Kuhn op. cit., 65.


Kuhn, ibid., 10.

Kuhn, ibid., 12.
Figure 1
Overview of Model Structure

[Diagram of model structure with nodes labeled jth paradigm, Puzzle-Solving, Confidence, Practitioners, and more detailed internal structure nodes such as Determination of Research, Anomaly Recognition, Puzzle-Solving, Attitudes Toward Paradigm, Ability to Recognize Anomalies, Comparison to Competitors, Recruitment, Defection, and Comparison to Competitors, connected by arrows indicating the flow of the model.]
Figure 2

Internal and External Determinants of Confidence in a Paradigm

- Anomalies
- Change in Confidence
- Solved Puzzles
- Puzzle-Solving Progress
- Receptiveness to Change in Confidence
- Total Solved Puzzles
- Solved Puzzles Relative to Competitors
- Anomalies Relative to Acceptable Level
- Anomalies Relative to Competitors
- Anomalies of Competitor Paradigms
- Solved Puzzles of Competitor Paradigms
Figure 3
The Puzzle-Solving Sector

Diagram:
- Puzzle Initiation and Abandonment Rate
- Puzzles Under Attack
- Anomaly Recognition Rate
- Puzzle Solving Rate
- Anomaly Resolution Rate
- Anomalies
- Solved Puzzles
Figure 4
Determinants of the Puzzle-Solving Rate
Figure 5

Determinants of the Anomaly Resolution Rate
Figure 6

Internal and External Determinants of the Recruitment and Defection of Practitioners
Figure 7

The first 1400 years of a simulation in which each new paradigm is created with randomly selected intrinsic explanatory power (the parameter C in equation 1). New paradigms are created stochastically, but the probability of creation is endogenous, as specified in equation (2).
Figure 8

Practitioners in Paradigms 8 and 13 through 17
Random Potential Explanatory Power

Figure 9

The Lifecycle of Paradigm 14
Figure 10. Two positive feedback loops that cause initially uncommitted and unorganized practitioners to coalesce into a highly focused paradigm (negative loops are not shown). Arrows indicate the direction of causality. Signs (+’ or ‘-) at arrow heads indicate the polarity of relationships: a ‘+’ indicates that an increase in the independent variable causes the dependent variable to increase above what it would have been, ceteris paribus (and a decrease causes a decrease). A ‘-’ indicates that an increase in the independent variable causes the dependent variable to decrease below what it would have been. That is, X -> ¹Y => (∂Y/∂X) > 0 and X -> ˘Y => (∂Y/∂X) < 0. Positive loop polarity [denoted by (+) in the loop identifier] indicates a self-reinforcing (positive feedback) process. Negative (-) loop polarity indicates a self-regulating (negative feedback) process.
Some of the positive feedback loops captured in the model which create path-dependent behavior. These loops rapidly differentiate paradigms which might initially be quite similar, and can amplify small fluctuations in local conditions to macroscopic significance. For clarity the negative loops in the system are not shown.
Table 1

Results of LOGIT regression. Variables characterizing the competitive environment at the time of emergence have a strong impact on the likelihood of success while the intrinsic explanatory power of a paradigm (C) has only a weak effect.

<table>
<thead>
<tr>
<th>Indep. Variable</th>
<th>Estimated Coeff.</th>
<th>Standard Error</th>
<th>t-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>5.44</td>
<td>0.52</td>
<td>10.42*</td>
</tr>
<tr>
<td>C</td>
<td>6.86e-4</td>
<td>4.34e-4</td>
<td>1.58</td>
</tr>
<tr>
<td>CPdom</td>
<td>-7.27</td>
<td>0.55</td>
<td>-13.19*</td>
</tr>
<tr>
<td>COMPET&lt;sub&gt;1&lt;/sub&gt;</td>
<td>-1.43</td>
<td>0.23</td>
<td>-6.17*</td>
</tr>
<tr>
<td>COMPET&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-4.99</td>
<td>0.52</td>
<td>-9.54*</td>
</tr>
<tr>
<td>COMPET&lt;sub&gt;3&lt;/sub&gt;</td>
<td>-13.52</td>
<td>50.00</td>
<td>-0.27</td>
</tr>
<tr>
<td>COMPET&lt;sub&gt;4&lt;/sub&gt;</td>
<td>-14.65</td>
<td>147.91</td>
<td>-0.099</td>
</tr>
</tbody>
</table>

N = 1026

* P<0.05
Table 2
Contingency table showing the model’s ability to predict whether a given paradigm rises to dominance. The model reduces the error rate in predicting dominance by half compared to chance.

<table>
<thead>
<tr>
<th>Actual</th>
<th>Non-dominant</th>
<th>Dominant</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-dominant</td>
<td>641</td>
<td>35</td>
<td>676</td>
</tr>
<tr>
<td>Dominant</td>
<td>135</td>
<td>215</td>
<td>350</td>
</tr>
<tr>
<td>Total</td>
<td>776</td>
<td>250</td>
<td>1026</td>
</tr>
</tbody>
</table>

$\lambda_b = .51; \text{ Proportion correct} = .83; \text{ Sensitivity} = .86; \text{ Specificity} = .83$
Figure 12

The probability a given paradigm rises to dominance as it depends on the confidence in the dominant paradigm at the time the new paradigm is created, and on the number of competitors the new paradigm faces. The estimated probabilities for paradigms facing the dominant paradigm and three or more other competitors are essentially zero.
For those paradigms that survive the emergence phase and rise to dominance, the duration of dominance is significantly related to their intrinsic explanatory power $C$ (eq. 1). However, there are two distinct clusters of paradigms, denoted Modes 1 and 2. Paradigms in mode 2, despite high intrinsic capability, dominate scientific endeavor for a far shorter time than paradigms in mode 1 with the same intrinsic capability. The difference is explained by differences in the competitive environment during the emergence phase of these paradigms. Not displayed in the plot is one paradigm with a duration of domination of 913 years and all the paradigms that never rise to dominance.