Modeling the Dynamics of Scientific Revolutions

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Introduction

Scholars have long attempted to understand the nature of scientific change. Is science characterized by the steady application of universally-accepted norms of logical inquiry, or is it an enterprise that periodically reconstructs itself from new fundamentals? One of the best-known examples of the latter view is Thomas S. Kuhn's *Structure of Scientific Revolutions*. Kuhn argues that new theories replace old ones rather than build upon them, and in the process revolutionize science's very image of itself (1962: 84-85). Scientific progress is seen not as a steady accumulation of truths, but "as a succession of tradition-bound periods punctuated by non-cumulative breaks" (Kuhn 1970: 208).

Kuhn's theory has had enormous influence in the social sciences, but it is also of enduring interest in the physical sciences (Barnes 1982; Lightman and Gingerich 1992). The notion of paradigm has, rightly or wrongly, been used to legitimate alternative methods of research as well as to delegitimate dominant modes of inquiry. Nonetheless, although 'paradigm competition' has become well-established in the academic lexicon, little is known about what such competition actually entails. How do internal and contextual forces interact to shape and constrain the development of new paradigms? Why do some paradigms last for centuries while others quickly wither?

Purpose

We address these questions with a formal dynamic model of paradigm competition. The model is based on Sterman's (1985) model of Kuhn, but modified to represent explicitly the competition among different paradigms. Although these models are inspired by 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 many simplifications. Indeed, making explicit the causal connections that we and others readers of Kuhn routinely take for granted has required the introduction of conjectures Kuhn might even disagree with (Wittenberg 1992; but see also Sterman 1992, Radzicki 1992 and Barlas 1992.) 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 important, 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. We see formalization as complementary to the work of philosophers and historians of science attempting to verify empirically theories of scientific change (e.g. Donovan, Laudan and Laudan, 1988). Second, Kuhn's theory is one example of a broader class of theories of revolutionary change. The model may provide insights into how revolutionary upheavals occurs in other domains such as the social sciences (see Kuhn, 1970: 208-209; Gersick, 1991, Tushman and Anderson 1986). Finally, the model applies nonlinear dynamics to sociological phenomena. It describes emergent processes, and model behavior is at all times path-dependent.

A Theory of Paradigm Development

Rather than summarize Kuhn's theory here, we assume familiarity with Kuhn's work and the many interpretations and alternatives to it (e.g. Lakatos and Musgrave 1976). An important aspect of Kuhn's theory for purposes of modeling is the life cycle of a "typical" 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. Such conduct characterized electrical research before the work of Franklin and his successors provided the field with a paradigm (Kuhn 1970: 13-15). Once a theory attracts nearly every scientist in the field – thereby becoming a dominant paradigm – normal science begins. Here scientists cease to debate fundamental methodological tenets, and, convinced that their paradigm is the proper way to characterize reality, proceed to apply it to nature's puzzles. When clashes between theory and reality do occur, they are more often than not resolved in favor of theory. Thus, for example, by the early twentieth century physics had become so identified with Newton's Principia that no one questioned Newton's theory even though there were persistent discrepancies between it and observations concerning the speed of sound and the motion of Mercury (Kuhn 1970: 81). A paradigm enters crisis when enough unsolved puzzles are recognized as important anomalies. Increasing numbers of scientists will devote their time to solving these anomalies rather than other puzzles, and some will propose radical solutions. A revolution occurs when a new paradigm based on such a radical idea is adopted, and science is reconstructed from new fundamentals. Einstein's theory of relativity is a well-known example of a revolutionary theory, in which basic notions of space and time were fundamentally reconceptualized. Obviously the timing, length, character, and context of each stage differ from case to case. For example, a dominant paradigm in crisis may quickly be replaced, or a crisis may deepen for decades as new theories fail to sprout or flower. The social, political and cultural context, as well as chance factors (the existence of an Einstein, Bohr or Keynes) may strongly condition the character and timing of the dynamics. Assessing the tension between situational and structural factors is one of the purposes of the model.

A Model of Paradigm Development

Sterman (1985) presents a dynamic model of Kuhnian paradigm change. The purpose of the model was to test the dynamic consistency of Kuhn's theory by assessing whether the causal processes Kuhn postulates can produce the dynamics he describes. To do so, the work deliberately focused on the internal dynamics of a single paradigm and ignored the explicit dynamics of competition. Wittenberg (1992) argued, however, that the model insufficiently accounts for paradigm competition. We thus construct a multi-paradigm model in which the structure of Sterman's model is replicated for each of the competitor paradigms, and additional structure is added to specify how paradigms interact.

The model creates a simulated ecology of interacting paradigms, each representing a community of practitioners, recruitment and defection from that community, as well as the intellectual activities of the members such as formulating and solving what Kuhn calls puzzles, recognizing and trying to reconcile anomalies, and conceiving new theories. The model accounts for attitudes and beliefs of the practitioners within each paradigm through constructs such as 'confidence in the paradigm' and the time required to recognize a phenomenon as an anomaly which challenges the theory.

The structure of Sterman's original (1985) model is retained with few modifications; readers are directed to that work for a complete description of the model structure. Here we provide a brief outline. The essence of Sterman's dynamic hypothesis is the notion that the average difficulty of the puzzles to be solved by the paradigm increases as the cumulative number of puzzles solved grows. This 'paradigm depletion' represents the idea that each paradigm is a limited model of reality which 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. Newtonian mechanics worked brilliantly for macroscopic, slow masses, but was harder to apply successfully to the domains of the very small or very fast. 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, initiating a self-reinforcing collapse as anomalies destroy confidence, and falling confidence increases the ability and willingness of practitioners to see the gaps in the theory.

The focal point of the model is a construct called 'confidence in the paradigm'. Confidence determines how anomalies are perceived, how practitioners allocate their research, and recruitment to and defection from the paradigm. It represents the basic beliefs of practitioners which structure reality, encompassing both logical, cultural, and emotional factors. Confidence is defined between 0 (absolute conviction the paradigm is false, nonsensical, superstition) 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. Confidence tends to decline when the number of anomalies exceeds an acceptable level, or when progress in puzzle-solving slows. The impact of anomalies and progress is mediated by the level of confidence itself. High levels of confidence preclude rapid changes in confidence because practitioners, utterly committed, resist 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 change their confidence if any significant evidence appears.

The external factors affecting confidence encompass the way in which practitioners in one paradigm view the accomplishments of other paradigms. We distinguish between the dominant paradigm, which we define as that paradigm commanding the allegiance of the most practitioners, and alternative paradigms. Confidence in an alternative paradigm tends to increase if its number of anomalies is less than that of the dominant paradigm, or if it has solved more puzzles. It tends to decrease if the dominant paradigm has fewer anomalies or more solved puzzles. Alternative paradigms compare themselves with one another as well as with the dominant paradigm. Confidence in an alternative paradigm tends to decrease if it has more anomalies or fewer solved puzzles than the largest of the other alternatives.

According to Kuhn, the normal science is puzzle solving. In the model, the rate at which scientists formulate and solve these puzzles are solved depends on the number of practitioners, the fraction of their time devoted to puzzle solving, and the intrinsic difficulty of the puzzles. Under normal conditions a puzzle, once formulated and attacked, will be solved in fairly short order, adding to the cumulative stockpile of knowledge generated by the paradigm. But as the intrinsic difficulty of puzzles grows, a growing number will resist solution long enough to be recognized as anomalies.

Anomaly recognition is a subtle psychological process, mediated in the model by confidence. Confidence influences the perception of anomalies in two ways. Confidence determines the degree to which practitioners are conditioned to see reality as consistent with their paradigm. Increases in confidence will slow the recognition of anomalies since practitioners are becoming more blinded by the paradigm, and thus take a longer time to recognize the problems that do arise as anomalies. Anomalies may sometimes be resolved into the theory, thus ending a potential threat to the paradigm. 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. 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 scientists are drawn into anomaly resolution in an attempt to solve the major outstanding problems challenging the theory, as for example the Michelson-Morley experiment drew forth many efforts to reconcile Newtonian theory with the constancy of the speed of light with respect to relative motion.

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. We assume for simplicity that the total population of scientists in all paradigms 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; it can easily be relaxed in future versions. Practitioners defect based on their confidence relative to the confidence of those in the dominant paradigm. 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 that will defect. The overall magnitude of the defection is determined by the number of practitioners in the paradigm. 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 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 measures the excitement, enthusiasm, and progress flowing from a successful endeavor – scientists are naturally drawn to outstanding examples of achievement.

The most significant difference between the original and present models is the explicit representation of 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 among 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 which are 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:

$$PA_t = p_{ps} * PPS_t + p_{ar} * PAR_t + p_{oa} * POA_t$$

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 which can form the basis for a new paradigm. Thus $p_{ar} > p_{oa} > p_{ps}$. 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 equal to .5 (neutral), a very small stock of solved puzzles and no initial anomalies. The newly launched paradigm must then compete for members against other existing paradigms and will succeed or fail to the extent it can (1) solve puzzles and resolve anomalies such that confidence in that paradigm grows; and (2) prove more attractive than other paradigms against which it might be competing. Note that it is possible, and indeed given the probabilities we assume, likely, that during a period of crisis, when many practitioners in the dominant paradigm abandon puzzle solving, that 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

In order to disentangle the internal and contextual factors underlying paradigm change we first present a simulation in which only one new paradigm may emerge out of the crisis of the previously dominant paradigm (figure 1). We assume the same high potential explanatory power used in Sterman (1985). We begin the simulation with a dominant paradigm in the full flower of normal science, with 100% of the practitioners committed to that paradigm, a high level of confidence, and few anomalies. However, as puzzles gradually become more difficult to solve, anomalies slowly accumulate, eventually leading to crisis and a drop in confidence. The new paradigm is created when confidence in the dominant paradigm falls below 0.7, in this case in year 124.75. Figures 2 and 3 illustrate the details of paradigm 2's life cycle. In the early period (years 125-170), confidence rises dramatically, since initial puzzle-solving progress is great and anomalies are low. The paradigm, initially untested, proves itself capable of solving puzzles, and thus attracts more practitioners, further boosting confidence. The virtuous circle of rising confidence, faster recruitment and puzzle-solving, leading to further boosts in confidence in the new paradigm bootstraps the new paradigm and accelerates the decay of the old as it is increasingly starved of practitioners, until the new paradigm dominates the entire field (about year 190), signalling the beginning of normal science organized around a different underlying metaphor, method, and metaphysics.

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 their paradigm, occurs approximately between years 190 and 300. As the paradigm is elaborated and solved puzzles grow, however, puzzles become more difficult to solve and anomalies slowly accumulate. Although the fraction of all practitioners committed to the paradigm remains high throughout the period, confidence peaks in year 240 and slowly falls, as does the fraction of practitioners engaged in sanctioned research (puzzle solving).

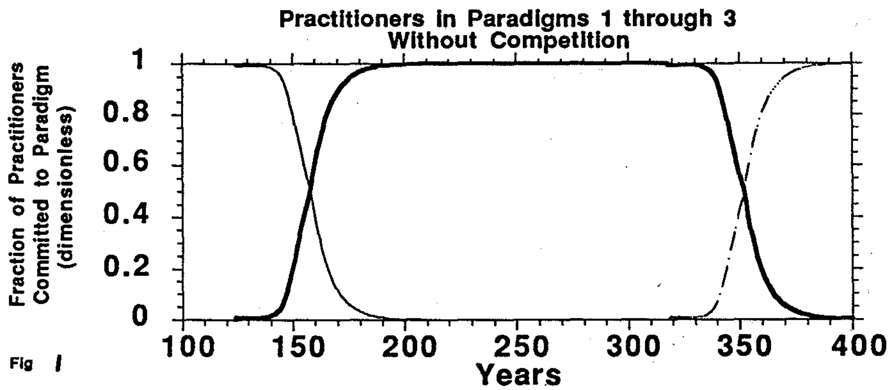

Fig 1

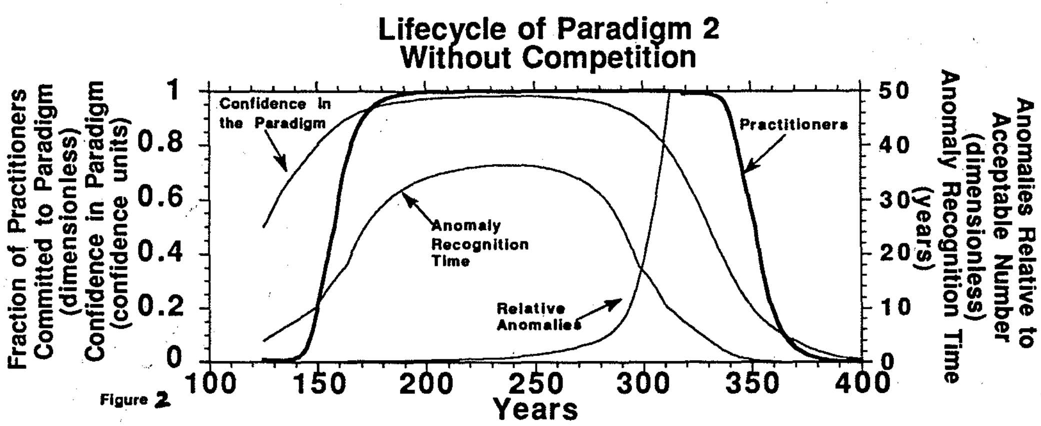

Figure 2

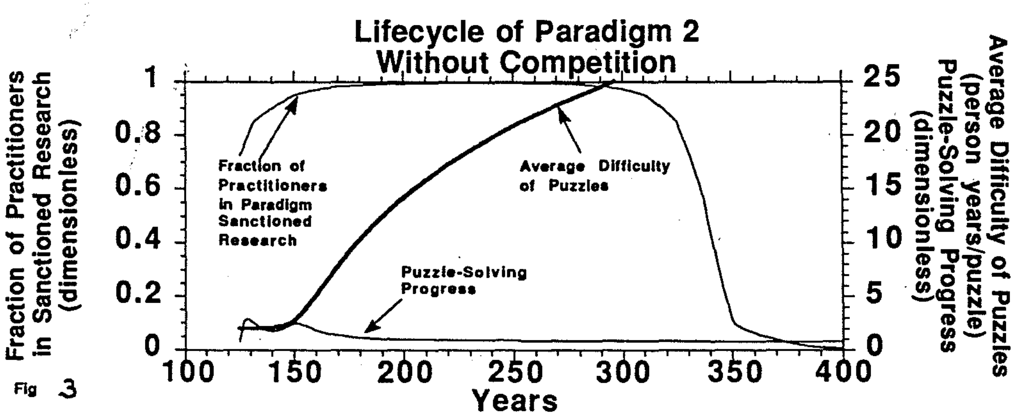

Fig 3

By year 300 the paradigm is in crisis due to high anomalies and slowing progress. The positive feedbacks which had previously caused membership to rise now cause it to decline. The progress of normal science has increased the difficulty of puzzles, since practitioners have begun to apply the paradigm beyond the scope for which it was created. This leads to an increase in anomalies, causing practitioners to leave puzzle-solving, eroding progress and decreasing confidence. Practitioners, increasingly sensitive to the paradigm's limitations, become more apt to see difficult puzzles as anomalies, thus further increasing anomalies and decreasing confidence in another positive feedback.

As the number of practitioners engaged in normal science falls and the number in anomaly resolution and other activities rises, the probability that a new paradigm will be created gradually grows. Around year 320 a new paradigm is in fact launched (figure 1). Since the new paradigm emerges during the crisis of paradigm 2, it quickly gains adherents while paradigm 2 loses members. Confidence and membership in paradigm 3 now accelerate sharply through the same processes at work earlier for paradigm 2, and the life cycle is completed as paradigm 2's confidence and membership fall eventually to 0. The many positive feedbacks described above create the self-organizing dynamic by which uncommitted and unorganized practitioners coalesce into a highly focused paradigm with productive normal science. The same positive 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 start to fall. Many if not most of these feedback loops involve processes internal to the paradigm. These loops were captured in the original model of Sterman (1985). In addition, having extended the model to explicitly account for competing paradigms, several additional positive loops which operate between competing paradigms are now represented (figure 4; note that the negative loops which ensure global stability are not shown). These loops reinforce the internal loops such that the overall behavior of a single paradigm going through its life cycle remains qualitatively similar to the original model.

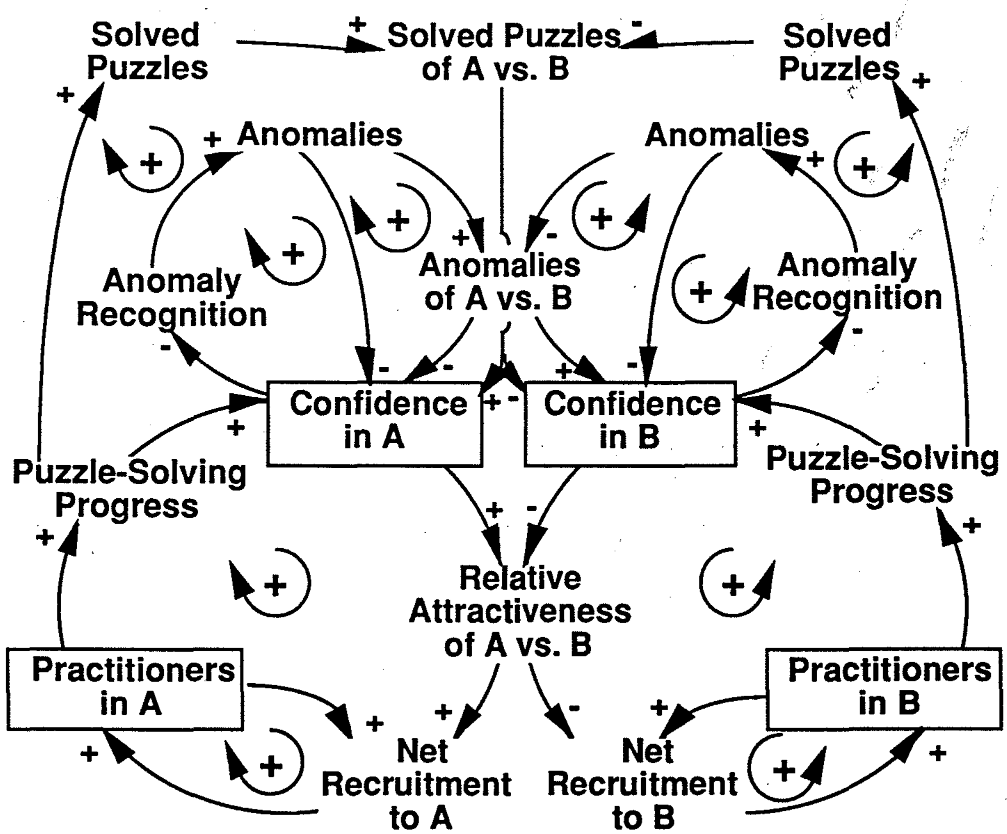

Figure 4. Some of the positive feedback loops captured in the model which create path-dependent behavior. These loops rapidly differentiate paradigms which might initially be quite similar, and can amplify small fluctuations in local conditions to macroscopic significance.

We now simulate the model with fully endogenous competition among paradigms. Figures 5 and 6 show a simulation incorporating both internal and competitive pressures. As in the first simulation, paradigm 1 is initialized in normal science, but now new paradigms are launched with a probability depending upon the vitality of the dominant paradigm. We further assume practitioners engaged in anomaly resolution have a greater likelihood of creating a new paradigm than those engaged in other activities, while practitioners in puzzle-solving are assumed never to produce a new paradigm. In these simulations the model is completely deterministic except for the probabilistic process by which new paradigms are created, and all paradigms have identical structure, parameters, and potential explanatory power.

The assumption that all new paradigms have the same potential explanatory power is deliberately made to highlight the processes of competition among newly launched contenders. In the simulation the crisis of a dominant paradigm may, depending on the random process governing paradigm creation, result in one or several new paradigms being launched within the crisis period when the probability of paradigm creation is large. Variations in the timing, length, and character of the life cycles across paradigms can only be due, therefore, to contextual factors, specifically the number and health of paradigms against which a newly created paradigm must compete.

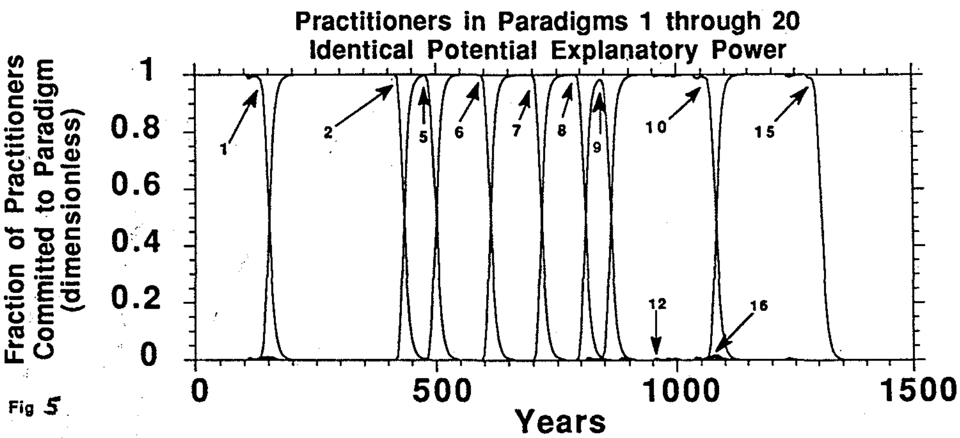

Fig 5

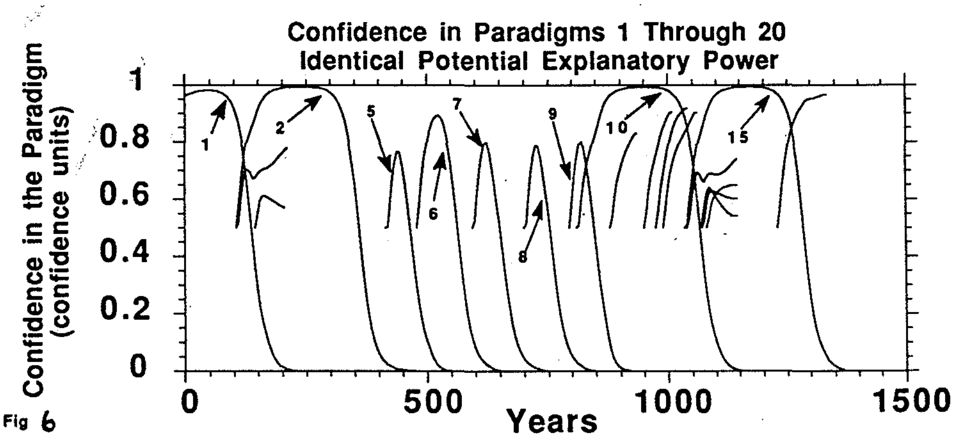

Fig 6

We simulate the model for 2000 years to lessen the influence of initial transients and to exhibit the range of possible fates for new paradigms. Figure 5 shows a succession of dominant paradigms in which the initial paradigm gives way to successors whose life cycles follow approximately the pattern seen in the previous simulation. Because the timing of paradigm creation is fully endogenous and stochastic, there is considerable variation in the lifetimes despite the equal explanatory power of all paradigms. Paradigm 2, for example, lives for 375 years, while paradigm 9 survives a mere 115.

What is most interesting about figure 5, however, is not what it displays but what it conceals. Not all new theories succeed. Paradigms 3, 4, 11-14 and 16- 20 never become dominant. Beneath the apparently orderly succession of paradigms seen in figure 5 lies considerable turmoil, as newly launched paradigms compete for dominance. Many face early extinction. Note the slight fluctuation in practitioners during the dominant phases of paradigms 1, 10 and 15, the telltale sign of paradigm candidates which are launched and rapidly fail. Figure 5 illustrates what Kuhn calls the invisibility of revolutions, where the linear and cumulative character of normal science portrayed in the textbooks conceals the messy, uncertain and contentious character of actual scientific practice (Kuhn 1970: 136- 143).

Consider paradigm 12, launched in year 951.25. In a world without competition it would grow as growth of solved puzzles and lack of anomalies raised confidence, thus attracting more recruits. However, paradigm 10 dominates science at the time and is far more attractive than the newcomer. Indeed, in year 950 paradigm 10 is still in the midst of normal science. With 10's greater numbers and higher confidence a new paradigm stands little chance of survival. By year 975 paradigm 12 is dead.

Consider now paradigms 15 and 16, launched in years 1039 and 1042.25, respectively. Although they emerge only 3.25 years apart, during paradigm 10's crisis, they suffer very different fates: paradigm 15 comes to dominate the field, while paradigm 16 perishes after a brief spurt. Here the contingency of outcomes on situational factors is decisive. Significantly, paradigm 15 does not succeed because of its head start in attracting practitioners: in year 1045 it actually has fewer than paradigm 16! The difference in their destinies lies in their levels of confidence. Consider the year 1055. Paradigm 15, though equal in size to paradigm 16, is more attractive to adherents of crisis-ridden paradigm 10 because its adherents, having had a 3 year lead over paradigm 16 in solving puzzles, have been able to consolidate and articulate their paradigm more coherently and persuasively than their chief rivals. The small advantage held by paradigm 15 at time 1055 is amplified as success begets success through the positive loops shown in figure 4. The greater the confidence of the paradigm, the more focused the puzzle-solving activity and the higher the rate of progress, further boosting confidence; the greater the confidence in the paradigm, the less able practitioners are to recognize anomalies, thus the lower the number of relative anomalies and the higher confidence becomes. The greater the confidence in the paradigm, the greater the recruitment of practitioners and the smaller the defection rate, increasing the size and political power of paradigm 15's community vis á vis paradigm 16, further benefiting paradigm 15 in the competition for resources, students, control of journals and conferences, and so on. By year 1105 paradigm 15 dominates science, while paradigm 16 has withered, and if remembered at all, is viewed as a blind alley, foolish error, or curiosity. Note that the death of paradigm 16 is not due to its intrinsic weakness, since it has the same puzzle-solving potential as paradigm 15 and all others.

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 feedback loop structure of the system as discussed above and highlighted in figure 4. The positive feedbacks which boost confidence and rapidly produce a focused community from a promising but incoherent new idea create the rapid growth of new paradigms as they bootstrap themselves into normal science. These same loops are responsible for the resistance of the dominant paradigms to challenges, as high confidence suppresses the creation and progress of any new theories. The same loops then create the accelerating collapse of the dominant paradigm once it begins to experience depletion of the root metaphor which defines it. The prevalence of positive feedback processes in the dynamics, however, means that contingent situational factors such as the number of practitioners in the dominant paradigm, their confidence level, the number of solved puzzles in anomalies of the dominant paradigm, as well as the number of other competing paradigms and their membership, confidence, and accomplishments strongly condition the fate of new paradigms. While it is obvious that the creation of a new theory is intrinsically unpredictable, the simulation shows clearly that the likelihood any given new paradigm grows to dominance or rapidly becomes extinct is strongly contingent on the environment into which it is launched-- an environment which in turn depends on the entire history of the paradigms which precede it. The prevalence of positive feedback processes in paradigm development and decay means that the evolution of the system as a whole is strongly path-dependent.

Although not explicitly modeled here, the fact that each new paradigm differs in intellectual content, possibly including fundamental epistemic and metaphysical assumptions, means that the succession of paradigms-- of world views-- is unpredictable, contingent on the prior history of science, and need not reflect an arrow of progress or even of consistency as paradigms of equal or even greater intrinsic "merit" may become extinct while weaker paradigms grow to dominance solely as a function of the context into which they are launched.

To illustrate, figures 7-8 show a simulation in which the intrinsic puzzle-solving capability of each paradigm is different. Specifically, the rate at which puzzle-solving becomes difficult as cumulative puzzles accumulate (the paradigm's "inherent potential") is chosen randomly. The evident differences in the duration of paradigm dominance cannot be explained solely by variation in the paradigms' intrinsic potentials. Thus, paradigms 13 and 18 have approximately the same potential, yet paradigm 13 outlives paradigm 18 by 175 years. The simulation shows how the context into which a new paradigm is launched may dominate its intrinsic puzzle solving capability. For example, paradigm 16, endowed with a potential approximately twice that of paradigm 13, fails because it is launched while paradigm 13 is still attractive enough to retain practitioners. Paradigm 16 is thus not able to recruit any practitioners and build a coherent body of knowledge. The sensitivity of outcomes to context is further exemplified by the fate of paradigm 17. It has less explanatory power than any one of the paradigm candidates 14 through 16, yet nonetheless becomes the successor to paradigm 13.

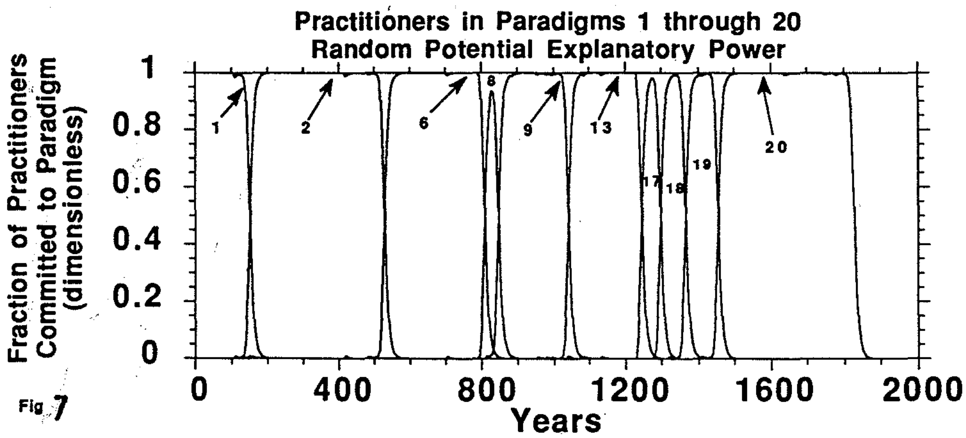

Fig 7

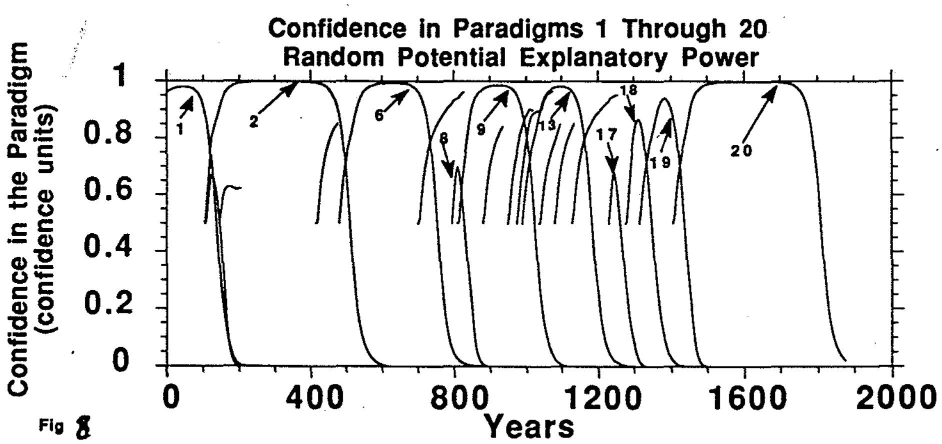

Fig 8

Conclusion

The present work extends Sterman's original (1985) model to portray explicitly the endogenous emergence of and competition with new paradigms. Results show that consideration of competing paradigms does not alter the essential dynamics of the paradigm life cycle, lending some confidence that the feedback processes captured in that model are robust in their ability to generate the collective behavior associated with emergence, normal science, crisis and revolution as Kuhn describes it. The addition of explicit competition among paradigms, however, adds significant new insight into the importance of situational contingencies in the succession of paradigms. Because paradigm growth and success are strongly conditioned by multiple positive feedback processes, historical contingencies can be decisive in determining which of several newly launched paradigms survives. The simulations show clearly that the health of existing paradigms at the time a new paradigm is launched, other initial conditions surrounding the emergence of a new theory, and inherently unpredictable events associated with a small number of individuals may be more important in determining the fate of any particular paradigm than its intrinsic explanatory power, logical force, or other 'rational' factors.

Indeed, the simulations show that historical context can easily cause a paradigm with greater ultimate potential to be eclipsed by a weaker one. The model thus identifies specific processes by which phenomena Kuhn highlights-- such as anticipations and the invisibility of revolutions – might arise. The model, however, is clearly highly simplified and cannot capture the full scope of sociological, intellectual, cultural, and other factors which impinge on activities as basic to society as scientific theory-building. We do not argue here that this model captures all the subtleties of Kuhn's theory, nor even that it represents a correct or comprehensive model of scientific activity. Plainly it does neither. Rather, we seek to demonstrate that it is both desirable and possible to capture in a formal model the causal hypotheses embodied in written theories of scientific endeavor which are alleged by their authors to produce the dynamics as those authors see them. The process of formalizing such hypotheses demands a discipline which surfaces 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 studies and other analyses. As in Sterman (1985), complete documentation of the model is available; we invite others to replicate, critique, revise, and extend the model to model and test views of scientific activity which differ from ours.

References

Barlas, Yaman (1992) Comments on 'On the very idea of a system dynamics model of Kuhnian science'. *System Dynamics Review.* 8(1), 43-47.

Barnes, Barry (1982) *T.S. Kuhn and Social Science.* New York: Columbia University Press.

Donovan, Arthur, Larry Laudan and Rachel Laudan, eds. (1988) *Scrutinizing Science.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gersick, Connie J.G. (1991) Revolutionary Change Theories: A Multilevel Exploration of the Punctuated Equilibrium Paradigm. *Academy of Management Review.* 16(1), 10-36.

Kuhn, Thomas S. (1962) *The Structure of Scientific Revolutions.* Chicago: University of Chicago Press.

-----. 1970. *The Structure of Scientific Revolutions. 2nd ed.* (Chicago: University of Chicago Press.

Lakatos, Imre and Alan Musgrave (1976) *Criticism and the Growth of Knowledge.* Cambridge: Cambridge University Press.

Lightman, Alan and Owen Gingerich (1992) When Do Anomalies Begin?, *Science*, 255, 7 February, 690-695.

Radzicki, Michael J. (1992) Response to 'On the very idea of a system dynamics model of Kuhnian science'. *System Dynamics Review.* 8(1), 49-53.

Sterman, John D. (1985) The Growth of Knowledge: Testing a Theory of Scientific Revolutions with a formal model. *Technological Forecasting and Social Change* 28(2),93-122.

Sterman, John D. (1992) Response to 'On the very idea of a system dynamics model of Kuhnian science'. *System Dynamics Review.* 8(1) 35-42.

Tushman, M. and Anderson, P. (1986) Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly*, 31, 439-465.

Wittenberg, Jason (1992) On the very idea of a system dynamics model of Kuhnian science. *System Dynamics Review.* 8(1) 21-33.