Competition and Succession in the Dynamics of Scientific Revolution

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Abstract

What is the relative importance of internal versus contextual forces in the birth and death of scientific theories? Elaborating on the analysis of a model of multiple paradigm competition and scientific development already developed by Wittenberg and Sterman, we find that situational factors present when a paradigm is launched largely determine a paradigm's probability of rising to dominance. Stronger paradigms that survive the emergence phase live longer than their weaker counterparts, but this too is contingent upon factors present during the emergence period.

Introduction

The publication of Thomas S. 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 uncontested triumph of ever more truthful and encompassing images of reality. In contrast, Kuhn argued that new theories replace old ones rather than build upon them, revolutionizing science's very image of itself (1970: 84-85). For Kuhn scientific development is fraught with errors, blind alleys, and intense competition among competing world-views. Progress is understood less as a steady accumulation of truths than "as a succession of tradition-bound periods punctuated by non-cumulative breaks" (Kuhn 1970: 208).

The idea that social, historically contingent factors might play a role in scientific development equal to that of a theory's intellectual content has elated social scientists and historians as much as it has infuriated many philosophers and scientists. For many social researchers Kuhn's theory legitimated resistance to the century-old attempt to make the study of society, politics and culture more 'scientific'. For many scientists and philosophers 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 interest in the nature of truth and the source of scientific commitment. Even the most ardent believer in scientific rationality must marvel at how "bad" explanations sometimes catch on while "good" ones languish for lack of interest. Even the most determined critic of Kuhn's theory must wonder how the Aristotelian paradigm, so demonstrably 'wrong' from the point of view of a Newtonian, could have dominated scientific thought for well over a millennium. Why is it that some paradigms last for centuries while others quickly wither? How do factors internal to a paradigm and contextual forces interact to shape and constrain the development of new paradigms?

Purpose

We address these questions with a formal dynamic model of paradigm competition. The model is based on Sterman's (1985) model of Kuhn's theory, which portrayed how internal factors could produce the collective behavior Kuhn identified as characteristic of scientific development. Wittenberg (1992) criticized this model for having excluded contextual and contingent elements such as the existence of competitor paradigms. Building upon this criticism, Wittenberg and Sterman (1992) extended the model to allow for explicit paradigm competition while still preserving the complex internal structure of the paradigm in Sterman's original model. In this paper we use the model to investigate the relative importance of internal and contextual factors in determining the fate of new paradigms.

Although this model remains 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 ibid.; 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 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. We see formalization as complementary to the work of philosophers and historians of science attempting to empirically verify theories of scientific change (e.g. Donovan, Laudan and Laudan, 1988). Kuhn's theory is also one example of a broader class of theories of revolutionary change.

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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, Sastry, 1992). Finally, the model applies nonlinear dynamics to sociological phenomena. It describes path-dependent processes in which new paradigms are endogenously and stochastically generated. Our results may thus contribute to the growing literature on evolutionary behavior (see Anderson, Arrow & Pines (1988); Bruckner, Ebeling and Scharnhorst (1989); Ebeling (1991); Bruckner, Ebeling and Scharnhorst (1990); Radzicki and Sterman (1993).)

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 1970). An important aspect of Kuhn's theory for purposes of modeling is the life cycle 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. Such conduct characterized electrical research before 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. Now scientists cease to debate fundamental issues, 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, 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 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.

A Model of Paradigm Development

We construct a multi-paradigm model in which the structure of Sterman's original (1985) model is replicated for each of the competitor paradigms, and additional structure is added to specify how the paradigms interact. The 1985 paper provides a complete description and documentation of the model structure for each paradigm; here we only outline that structure. 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 nature's 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 phenomena which challenge the theory such as anomalies. The essence of the 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. Specifically, the average difficulty of new puzzles to be solved, D, is given by

$$D=(SP/C)^{\gamma} \qquad (1)$$

where SP is the cumulative number of solved puzzles, C, the nominal solved puzzle reference, determines the intrinsic capability of each paradigm, and γ is the rate at which difficulty rises with cumulative progress (γ=1 here). Small values of C mean paradigm's intrinsic explanatory power is weak – the difficulty of new puzzles rises rapidly as normal science proceeds. Large values indicate a powerful paradigm, one that can explain a great deal before it becomes harder to apply. 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 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'. Confidence captures the basic beliefs of practitioners regarding regarding the epistemological status of their paradigm– is it seen as a provisional model or revealed truth?

Encompassing logical, cultural, and emotional factors, confidence determines how anomalies are perceived, how practitioners allocate research effort, and recruitment to and defection from the paradigm. It is defined between 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. 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, 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 in the face of anomalies.

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, 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. 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 most successful of the other alternatives.

According to Kuhn, normal science is puzzle-solving. In the model, the rate at which scientists formulate and solve these puzzles 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. 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 become increasingly 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. For example, the Michelson-Morley experiment drew forth many efforts to reconcile Newtonian theory with the observed 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. 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.

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:

$$PA_t = p_{ps} \cdot PPS_t + p_{ar} \cdot PAR_t + p_{oa} \cdot POA_t \tag{2}$$

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 $p_{ar} > p_{oa} > p_{ps}$. 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 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. 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 many practitioners in the dominant paradigm abandon puzzle-solving, and newly created paradigms will vie for ascendancy not only against the dominant paradigm but against one another.

Exploring the Dynamics of Paradigm Development

The results presented in Wittenberg and Sterman (1992) confirm that consideration of competing paradigms does not alter the essential dynamics of the paradigm life cycle as laid out in Sterman (1985). Readers are referred to the former paper for a complete description of this replication. Figures 1a and 1b illustrate a simulation with fully endogenous competition among paradigms. Paradigm 1 is initialized in the midst of normal science, and new paradigms are launched stochastically, with a probability depending upon the vitality of the dominant paradigm. 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. Otherwise all paradigms have identical structure and parameters.

Figure 1 shows 1400 years of a simulation. The simulation yields a succession of dominant paradigms in which the initial paradigm gives way to successors whose life cycles vary in their length, timing and character. What is most interesting is not what the figures display but what they conceal. Not all new theories succeed. Beneath the apparently orderly succession of paradigms lies considerable turmoil. As evident in figure 1a, paradigms 2-4, 7, 9-12, 15, 17-18 never become dominant. Many new theories face early extinction. Figures 1a and 1b illustrate 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). The simulation replicates the 'punctuated equilibrium' pattern described by Kuhn.

Does the fate of a new paradigm depend on its intrinsic potential to explain nature or on situational contingencies surrounding its birth? Does "truth" eventually triumph as better theories defeat inferior ones, or is timing everything? Consider paradigms 8 and 9, launched around years 199 and 203, respectively. Although they emerge only about 4 years apart, during the crisis of paradigm 5, they suffer very different fates: paradigm 8 comes to dominate the field, while paradigm 9 eventually perishes. Here the contingency of outcomes on situational factors is decisive. Significantly, paradigm 8 does not succeed because of its 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: paradigm 9 has a potential 13% *greater* than paradigm 8. The difference in their destinies lies in their levels of confidence. Consider the year 212. Paradigm 8, though equal in size to paradigm 9, is 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 consolidate and 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 2). Paradigm 8 eventually dominates science, while paradigm 9 slowly fades into obscurity. If it is remembered at all, it is viewed as a blind alley, foolish error, or curiosity.

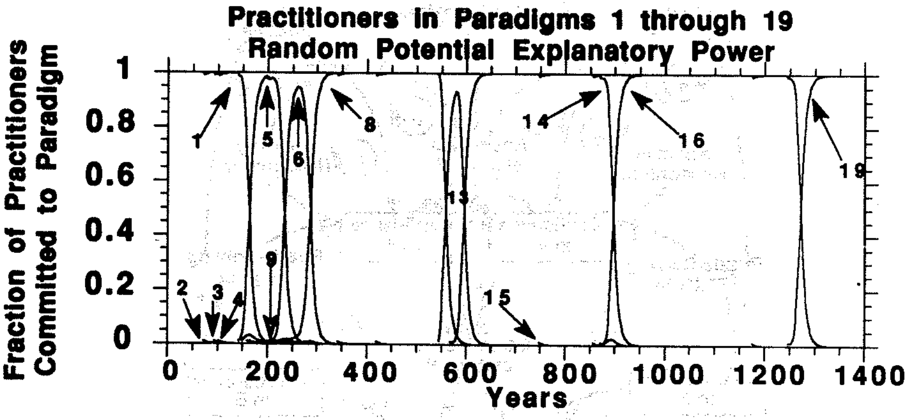
Practitioners in Paradigms 1 through 19
Random Potential Explanatory Power

Figure 1a

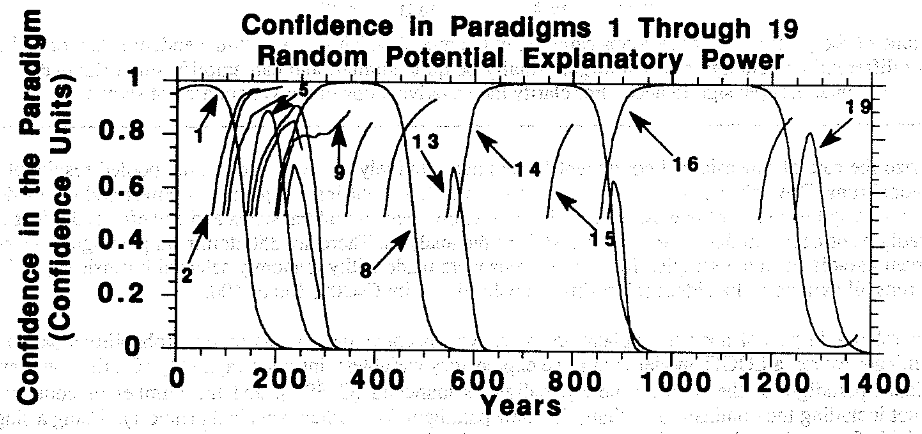
Confidence in Paradigms 1 Through 19
Random Potential Explanatory Power

Figure 1b

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. Figure 2 shows some of the positive feedback loops that act to differentiate competing paradigms (the many negative loops are not shown). These positive feedbacks boost confidence and rapidly produce a focused community from a promising but incoherent new idea. They give a paradigm with an initial advantage an edge in recruitment of new members, leading to still greater advantage. 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. Once a dominant paradigm begins to experience depletion of the root metaphor which defines it these same loops accelerate the collapse. The prevalence of positive feedback processes in the dynamics means that historical contingencies such as the number of practitioners in the dominant paradigm, their confidence level, the number of solved puzzles and anomalies of the dominant paradigm, as well as the number of 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 history of the paradigms which precede it. The prevalence of positive feedback processes in paradigm development means that the evolution of the system as a whole is strongly path-dependent.

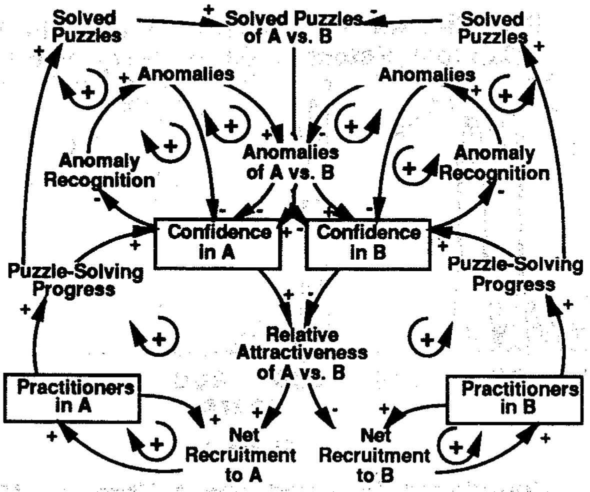

Figure 2. Some of the positive feedback loops captured in the model which create path-dependent behavior. These loops rapidly differentiate paradigms which might initially be quite similar, and can amplify small fluctuations in local conditions to macroscopic significance. For clarity the negative loops in the system are not shown.

To characterize the role of intrinsic and contingent factors quantitatively, we now present the pooled results of 57 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 withy randomly selected intrinsic capability, C. In some runs all paradigms had identical intrinsic capabilities, with C=200, 300 or 400.

To assess the relative impact of intrinsic explanatory power versus contextual factors on the probability a paradigm becomes dominant we ran 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) that new paradigm faces when launched (Table 1). Using a single (ordinal) variable for number of competitors implies that moving from one competitor to two has the same effect on the probability of dominance as moving from two to three. We thus 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.

$$P_t(\mathrm{Dom}) = 1/(1+\exp(-(b_0 + b_1 C + b_2 CP_t^{dom} + \sum_{i=1}^{4} w_i COMPET_i))) \tag{3}$$

where the t subscript indicates that the probability is calculated at the launch time of the new paradigm.

Indep Variable	Estimated Coeff	Standard Error	t-statistic
Constant	5.44	0.52	10.42*
C	6.86e-4	4.34e-4	1.58
CP^{dom}	-7.27	0.55	-13.19*
$COMPET_1$	-1.43	0.23	-6.17*
$COMPET_2$	-4.99	0.52	-9.54*
$COMPET_3$	-13.52	50.00	-0.27
$COMPET_4$	-14.65	147.91	-9.91e-2

* $P<0.05$ Number of observations = 1026

Table 1

LOGIT models are more difficult to evaluate than standard regression models because we have no actual probabilities of dominance with which to compare our predicted values: in the model paradigms either become dominant or do not. We thus compare the actual distribution of non-dominant and dominant paradigms with the distribution predicted by the model. Here a predicted probability of dominance greater than 50% is interpreted as a prediction of dominance. If this probability is less than or equal to 50% it is considered a prediction of failure. Table 2 displays a 2x2 matrix of how well the model predicted actual successes and failures.

		Predicted		
		Non-dominant	**Dominant**	**Total**
Actual	**Non-dominant**	641	35	676
	Dominant	135	215	350
	Total	776	250	1026

$\lambda_b = 0.51$

Table 2.

For any paradigm picked at random our best guess of whether it was dominant or non-dominant (without knowing the values of C, CP^{dom} and $COMPET_i$) would be that it was non-dominant, since fully 66% of all paradigms never dominate. The statistic $\lambda_b = 1-((errors|model)/(errors|no\ model))$ measures how much the model improves the accuracy in predicting whether a paradigm becomes dominant compared to the chance error rate. Using these explanatory variables reduces the error rate by half, a substantial improvement.

The values of the individual coefficients illustrate the relative weakness of intrinsic capability in comparison with the contextual factors in determining whether a paradigm becomes dominant. Although the magnitudes of the estimated C and CP^{dom} coefficients can not be directly compared because they are measured in different units, we can still get a sense of their relative impact. The maximum value C can take is 800, so its maximum input into the LOGIT equation is (.000686)(800)=0.55. The value CP^{dom} would have to take to offset the impact of C = 0.55 is 0.55/7.27 = .08. Thus whenever $CP^{dom}>0.08$, its contribution to a new paradigm's probability of dominance exceeds the greatest contribution C could ever make. Given that only a little over 7% of all paradigms are launched with $CP^{dom}<0.1$, the influence of CP^{dom} will outweigh that of C in most cases. Figure 3 best illustrates the relative importance of the contextual factors CP^{dom} and the number of competitors compared to intrinsic capability.

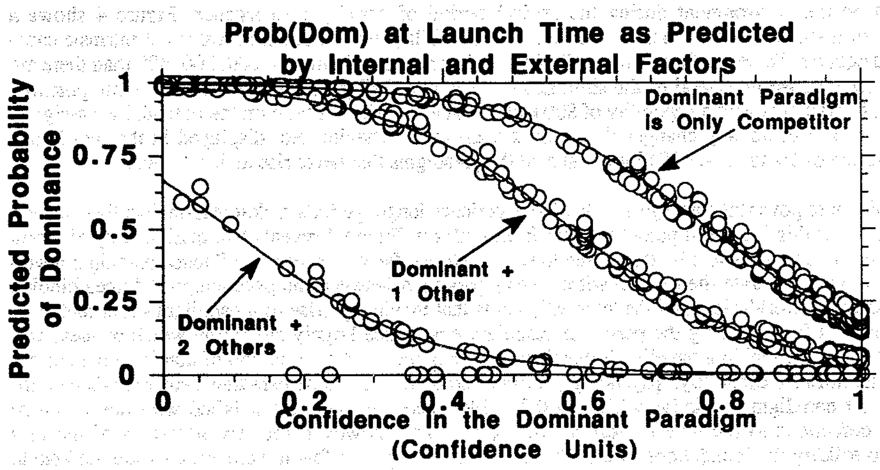

Figure 3

The values along the y-axis of figure 3 are the predicted probabilities of paradigm dominance generated by the LOGIT in equation 1. The value along the x-axis is confidence in the dominant paradigm at the time the new paradigm is launched. 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 CP^{dom} varies over the [0,1] interval, for each number of competitors and assuming intrinsic capability takes on its mean value $C_{avg} = 371.4$; that is:

$$P_t(Dom) = 1 / (1 + \exp(-(5.44 + .000686C_{avg} - 7.27CP^{dom} + w_i))). \tag{4}$$

For paradigms launched into a field with only the dominant paradigm, the probability of dominance is given by the curve in the upper-right. Curves are also displayed for settings with one and two other competitors. The curve for four competitors has probabilities ≈ 0. For all but the smallest values of CP^{dom}, the greater the number of competitors, the less likely a new paradigm becomes dominant. Likewise, the greater the value of CP^{dom}, the less likely a new paradigm is to become dominant. The regression results and figure 3 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 CP^{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 CP^{dom} is between about 0.6 and 0.8 the new paradigm is more than likely 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 3 also underscores the virtual irrelevance of internal factors in determining a paradigm's probability of dominance. The data fall very close to the predicted values. Departures from these curves represent the added impact of intrinsic capability as a predictor of dominance. Capability has an effect approaching that of the number of competitors only when CP^{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 is overwhelmingly determined by historical contingencies and only weakly influenced by its intrinsic explanatory power (its "truth"). 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 2).

While context determines the likelihood a given new theory will rise to dominance, how do internal and contextual factors interact to determine how long successful paradigms dominate their field? Do intrinsically powerful paradigms remain dominant longer than their weaker counterparts? Although intrinsic capability exercises a much greater influence over the duration of domination than it does over the probability of dominance, the effect is still highly conditioned on the environment during the critical period of paradigm emergence. Figure 4 shows a paradigm's duration of domination as a function of its intrinsic capability. Note that not all values of intrinsic capability have occurred equally. There are far more paradigms with intrinsic capabilities of 200, 300, 400 than there are with other capabilities because in several of the simulations we required all paradigms to have the same potential power. The cluster of paradigms with a capability of 800 reflects an arbitrarily-set limit on the potential we assign to new paradigms. This limit in no way changes the model's qualitative behavior. 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.

Although intrinsically more powerful paradigms do tend to experience longer periods of domination than their weaker counterparts, the effect of this increased potential is far from uniform. Figure 4 reveals two qualitatively different modes of behavior, each distinguishable by the degree to which internal factors appear to influence paradigm development. These two modes illustrate the tension within every paradigm between the psychological forces binding practitioners to a particular world-view and the 'rational' doubts that inevitably arise as a paradigm's root metaphor begins to fail. Contextual forces during the period of paradigm emergence largely determine which of these two internal factors is more influential in a paradigm's development. In mode 1, where duration of dominance increases relatively steeply with intrinsic capability, psychological forces predominate. These paradigms emerge when confidence in the dominant paradigm is relatively high (> 0.8). Most scientists are still satisfied with the dominant paradigm, slowing defections to the new paradigm. During this time, however, the few adherents of the new paradigm are able to solidify the foundations of their theory. Because they are few in number, they are not able to solve puzzles so rapidly that the limits of their paradigm are reached. Anomalies grow very slowly as increasingly confident practitioners solve relatively easy puzzles. Their confidence rises. By the time practitioners in the dominant paradigm finally do become disaffected, the initial adherents will have articulated the new paradigm 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 fulfill its intrinsic potential.

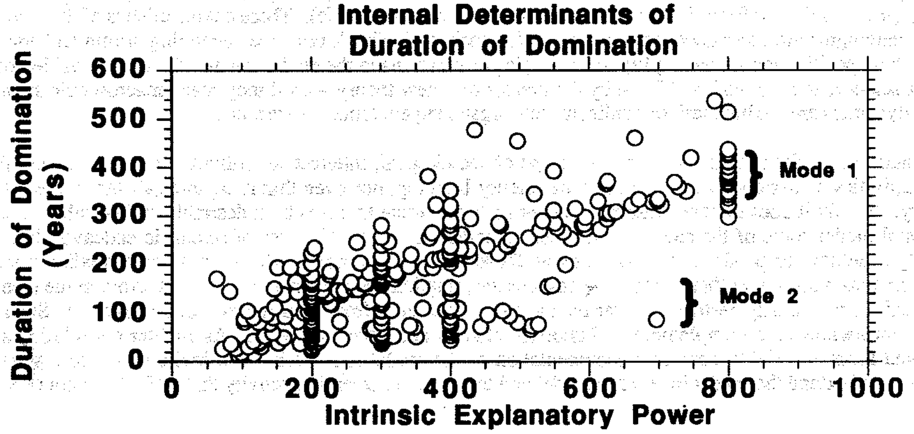

Figure 4

'Rational' factors predominate in the development of paradigms in mode 2. These paradigms emerge when confidence in the dominant paradigm is already quite low (usually < 0.4). The new contender enters a field in which practitioners are doubting the dominant paradigm, but still have not found a more attractive alternative. Thus, as uncertain as the new paradigm is, it nonetheless quickly wins new members. The rapid influx of new practitioners means the rate of puzzle solving will be high. The underlying metaphor defining the paradigm will be extended rapidly into new terrain, and the average difficulty of puzzles starts to rise, increasing the number of puzzles likely to be seen as anomalies. Further, the influx of new practitioners occurs at a time when confidence is low, meaning basic disagreements about the methods, data, and criteria of validity for the theory still persist. Without normal science, without the acculturation and perceptual filters provided by the world view of a well-articulated paradigm, anomalies and disagreements arise at an alarmingly high 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.

Conclusion

The present work extends Wittenberg and Sterman's (1992) analysis of paradigm creation and competition. Results show that the importance of situational contingencies found in the earlier work is robust over many runs of the model and widely varying values of intrinsic explanatory power. The confidence of practitioners in the old paradigm and the number of other new competitors determine whether a new theory will rise to dominance or quickly perish. The eclipse of potentially strong paradigms by inherently weaker ones is thus not a pathological outcome, but rather a normal part of scientific progress as we have modeled it.

The interplay between inherent 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 will 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 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 thus persisting until the anomalies that do cause revolution, in Kuhn's words, "penetrate existing knowledge to the core."

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 infant mortality rate for paradigms seems to depend almost entirely on the environmental conditions at the time of birth. This is a sobering conclusion, 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 (see Gould 1990 for a similar view applied to the evolution of life). 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 unobservable, local conditions of science, society, and self faced by the creator of a new theory – until they reach macroscopic significance. Such dynamics are the hallmark of nonlinear, self-organizing evolutionary systems.

We do not claim the model encompasses the full scope of sociological, intellectual, cultural, and other factors that impinge on activities as basic to society as scientific theory-building, nor even that it captures all the subtleties of Kuhn's theory. Plainly it does neither. Rather, we seek to demonstrate that it is both desirable and possible to capture in a formal model some of the causal hypotheses embodied in written theories of scientific endeavor that are alleged by their authors to produce the dynamics as those authors see them. The process of formalizing such hypotheses demands a discipline that 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) and Wittenberg and Sterman (1992), complete documentation of the model is available; we invite others to replicate, critique, revise, and extend the model in order to model and test views of scientific activity that differ from ours.

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