Self-Organization, 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? We describe a dynamic model of the birth, evolution, and death of scientific paradigms based on Thomas Kuhn's *Structure of Scientific Revolutions*. The model creates a simulated ecology of interacting paradigms in which the creation of paradigms 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 present when a paradigm is created 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 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.

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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 (e.g. Lightman and Gingerich 1992, Hoyningen-Huene 1993). 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 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 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 verify theories of scientific change empirically (e.g. Donovan, Laudan and Laudan, 1988). 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 (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 formal models of evolutionary behavior in human and other systems, for example Anderson, Arrow & Pines (1988), Bruckner, Ebeling and Scharnhorst (1989), Ebeling (1991), Bruckner, Ebeling and Scharnhorst (1990) and Radzicki and Sterman (1993).

A Theory of Paradigm Evolution and Succession

Rather than summarize Kuhn's theory here, we assume familiarity with Kuhn's work and the many interpretations and alternatives to it. (Kuhn's work has led to literally hundreds of interpretive and critical analyses. Hoyningen-Huene [1993] provides a critical assessment and the most recent survey and bibliography; see also Lakatos and Musgrave [1970]). An important aspect of Kuhn's theory for purposes of modeling 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. Such conduct characterized electrical research before Franklin and his successors provided the field with a paradigm (Kuhn 1970: 13-15). As a theory attracts nearly every scientist in the field – thereby becoming a dominant paradigm – normal science begins. Now 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 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).

Normal science continues until a crisis arises. 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 may 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.

The Model

Dynamic Hypothesis: Paradigms are extended metaphors. 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 heart of the 1985 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 that 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" (1968, p. 80). C.M. Turbayne (1970) 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" (1970, p. 113). Second, metaphor involves a "transfer of schema" from one area of experience to another (see Goodman 1968, pp. 71-80). Consider the metaphor "the brain is a computer." The characteristics of a computer are transferred, via the metaphor, to the brain. The metaphor works because the characteristics of computers are well known and carry a constellation of meanings and examples that illuminate characteristics of the brain. For Kuhn paradigms operate similarly: scientists are taught to transfer familiar models to new puzzles, to "grasp the analogy" (Kuhn 1970, p. 189). 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, relegating the rest to irrelevance. 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" (1970, p.15). 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" (1954-1955, pp. 284-285). Kuhn attributes the same power to paradigms:

> The historian of science may be tempted to exclaim that when paradigms change, the world itself changes with them. Led by a new paradigm, scientists adopt new instruments and look in new places....[They] see new and different things when looking with familiar instruments in places they have looked before. Insofar as their only recourse to the world is through what they see and do, we may want to say that after a revolution scientists are responding to a different world (1970, p. 111).

As powerful as metaphors are, they are inherently limited, and if pushed too hard will strain and crack. As a trite 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. Newtonian mechanics worked brilliantly for macroscopic, slow masses, but was harder to apply successfully to the domains of the very small or very fast. Anomalous results such as the repeated failure to detect drift through the ether were instrumental in the paradigm's eventual decline (Kuhn 1970, pp. 73-74).

Thus the central dynamic hypothesis behind the model draws on the notion that paradigms are extended metaphors, and that metaphors are not unlimited in their applicability to reality. The essence of the model is the hypothesis 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. The formalization of this hypothesis is described below.

Unlike the original model, the current 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 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 and stock-and flow structure of the model (see also Sterman 1985). Note that each paradigm has the same internal structure and that there are structurally identical flows among paradigms. 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 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 (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, 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 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. 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.

Puzzle Solving: According to Kuhn, normal science is puzzle-solving. The puzzle-solving sector is shown in figure 3. Three categories of puzzles are distinguished. Solved puzzles and anomalies are self-explanatory. The third category, puzzles under attack, consists of those puzzles that are formulated and actively under study, but which have not yet yielded or been recognized as anomalies. Four flows connect the different categories. 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. 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.

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 much far the root metaphor defining the paradigm had 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

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

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 majority of practitioners will usually be involved in puzzle-solving, while some will be working to resolve anomalies, and others may be trying to come up with alternatives or doing some other kind of work. Those involved in puzzle-solving and anomaly resolution make up the fraction of practitioners in paradigm-sanctioned research, a function of confidence in the paradigm. The higher the confidence, the greater fraction of practitioners involved in sanctioned research.

Anomaly recognition is a subtle psychological process. Anomalies are not simply experiments that run counter to expectation. There are always disagreements between fact and theory. Only when normal science repeatedly fails to resolve the differences or to explain some novelty does a puzzle become recognized as an anomaly. The only difference between an unsolved puzzle and an anomaly is the length of time it has resisted resolution. Confidence determines the degree to which practitioners are conditioned to see reality as consistent with their paradigm. Thus, the fraction of puzzles recognized as anomalies depends on the balance between the average time required to solve a puzzle, a function of the average difficulty of puzzles, and the time required to recognize an anomaly, a function of practitioners' confidence in the paradigm. Rising confidence slows 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 before they are solved as practitioners' skepticism and doubts grow.

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 scientists are drawn into anomaly resolution in an attempt to solve the major outstanding problems challenging the theory. Kuhn notes that most practitioners are reluctant to work on anomalies. The vast majority prefer the relative safety and professional rewards of puzzle-solving.

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. We assume for simplicity that 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; it can easily be relaxed in future versions. 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 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 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:

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

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 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 (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 the newly created paradigms will vie for ascendancy not only against the dominant paradigm but against one another.

Exploring the Dynamics of Paradigm Development

Figures 7a and 7b 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 (truncated such that $C \leq 800$; eq. 1). Otherwise all paradigms have identical structure and parameters.

Figures 7a and 7b show the first 1400 years of a simulation. The simulation yields a succession of dominant paradigms in which the initial paradigm gives way to successors which go through the typical lifecycle as described by Kuhn, but whose lifecycles vary 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. 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 messy, uncertain and contentious character of actual scientific practice (Kuhn 1970: 136-143). The simulation replicates the 'punctuated equilibrium' pattern described by Kuhn.

The role of internal factors underlying a paradigm's evolution is 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. However, as puzzles gradually become more difficult to solve anomalies slowly accumulate, 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). Paradigm 13 has a very low inherent potential, so that its rapid rise to domination by around year 580 is matched by an equally rapid drop, as its practitioners quickly exhaust the very limited potential of its underlying metaphor. Paradigm 14 benefits from the early demise of paradigm 13. The graphs in figure 9 illustrate the details of paradigm 14's lifecycle. In the early period (years 566 to 610), 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 self-reinforcing feedback of rising confidence, faster recruitment and puzzle-solving, leading to further boosts in confidence and the suppression of anomalies accelerates the decay of paradigm 13 and bootstraps paradigm 14 into dominance by around year 625, its metaphor, method and metaphysics triumphant over the now-discredited paradigm 13. These positive feedback loops are illustrated in figure 10.

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. New paradigms might emerge during this period, such as paradigm 15 just before year 750 (figure 8), but they usually perish in the face of competition with the supremely confident dominant paradigm. Paradigm 15 is quashed within a few years. Yet as paradigm 14 is elaborated and solved puzzles grow, puzzles slowly become more difficult to solve and anomalies accumulate. Although the fraction of all practitioners committed to the paradigm remains high throughout the period, confidence begins to fall 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 it to collapse. 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.

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 paradigm emerges during the crisis of paradigm 14, it quickly gains adherents while paradigm 14 loses members. Confidence and membership in paradigm 16 now sharply accelerate through the same processes at work earlier for paradigm 14 (and 13 as well), and the cycle is completed as paradigm 14's confidence and membership eventually fall to 0. What was once uncontested Truth is now seen as primitive error. Paradigm 17, launched around year 870, is quickly crushed by the surging 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 productive normal science. 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. These results confirm that for those paradigms that survive, consideration of competing paradigms does not alter the essential dynamics of the paradigm lifecycle as laid out in Sterman (1985).

However, consideration of competition and succession among paradigms is essential to address many important questions. Why do some paradigms rise to dominance while others quickly wither? 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 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, 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. 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 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 10). 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.

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 11 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. 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 a the gap in confidence to widen even further. The self-reinforcing differentiation 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 progress of any 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 in normal science make it unlikely for the new theory to 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.

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 that, once created, 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.

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 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). 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:

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

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

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 shows how well the model predicted actual successes and failures.

For any paradigm picked at random our best guess of whether it was dominant or non-dominant (without knowing the values of C, C^{Pdom} and $COMPET_i$) would be that it was non-dominant, since fully 66% of all paradigms never dominate. The statistic λ_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 regression results (table 1) show that all the coefficients have the predicted signs. 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 relative weakness of intrinsic capability in comparison with the contextual factors in determining whether a paradigm becomes dominant. Although the magnitudes of the estimated coefficients for C and C^{Pdom} 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 C^{Pdom} would have to take to offset the impact of C = 0.55 is 0.55/7.27 = .08. Thus whenever C^{Pdom}>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 C^{Pdom}<0.1, the influence of C^{Pdom} will outweigh that of C in most cases. Figure 12 best illustrates the relative importance of the contextual factors C^{Pdom} and the number of competitors compared to intrinsic capability.

The values along the y-axis of figure 12 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:

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

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 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 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 12 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 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 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 10).

While context determines the likelihood a given new theory will rise to dominance, how do internal and contextual factors interact to determine how long those paradigms that are successful 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 13 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.

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 13 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 puzzle difficulty grows before the theory is in place to approach difficult phenomena. 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 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.

'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 effort is 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 the acculturation and perceptual filters provided by the world view of a well-articulated paradigm, anomalies and disagreements 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. Thus while intrinsic potential is strongly related to longevity for those paradigms that succeed, contextual factors even here are critical.

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" (1970, p. 65).

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 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 (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 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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Figure 1

Overview of Model Structure

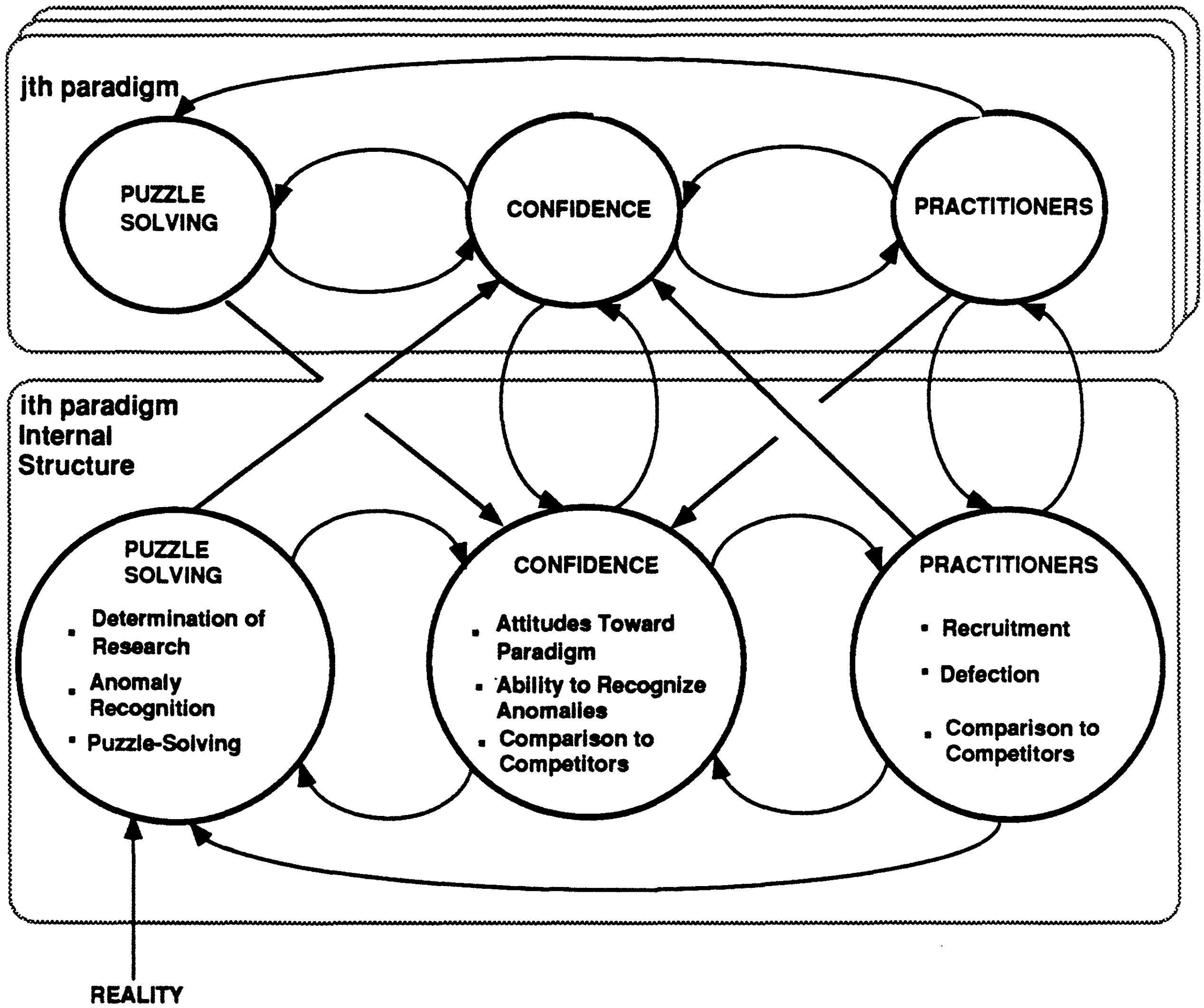

Figure 2

Internal and External Determinants of Confidence in a Paradigm

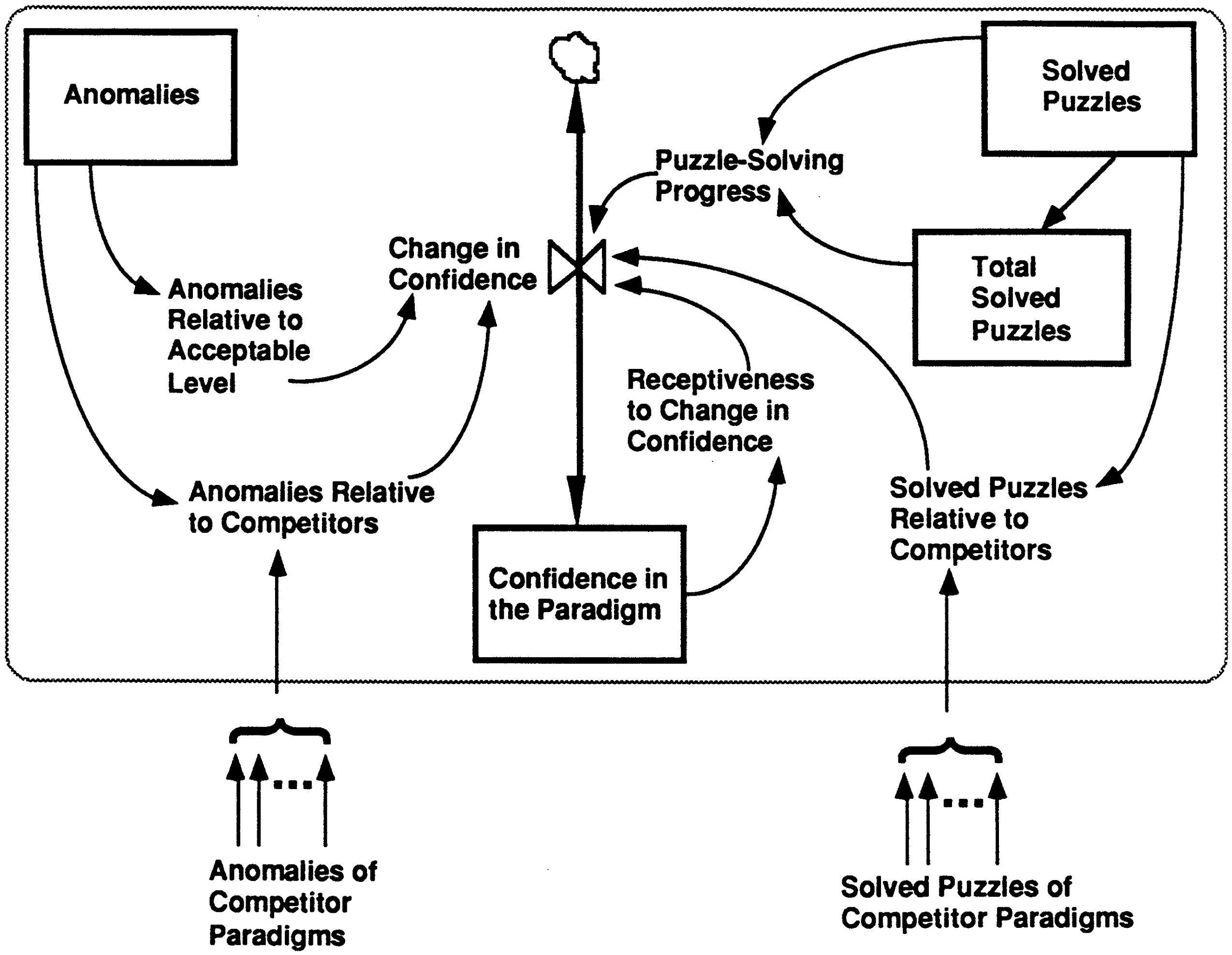

Figure 3

The Puzzle-Solving Sector

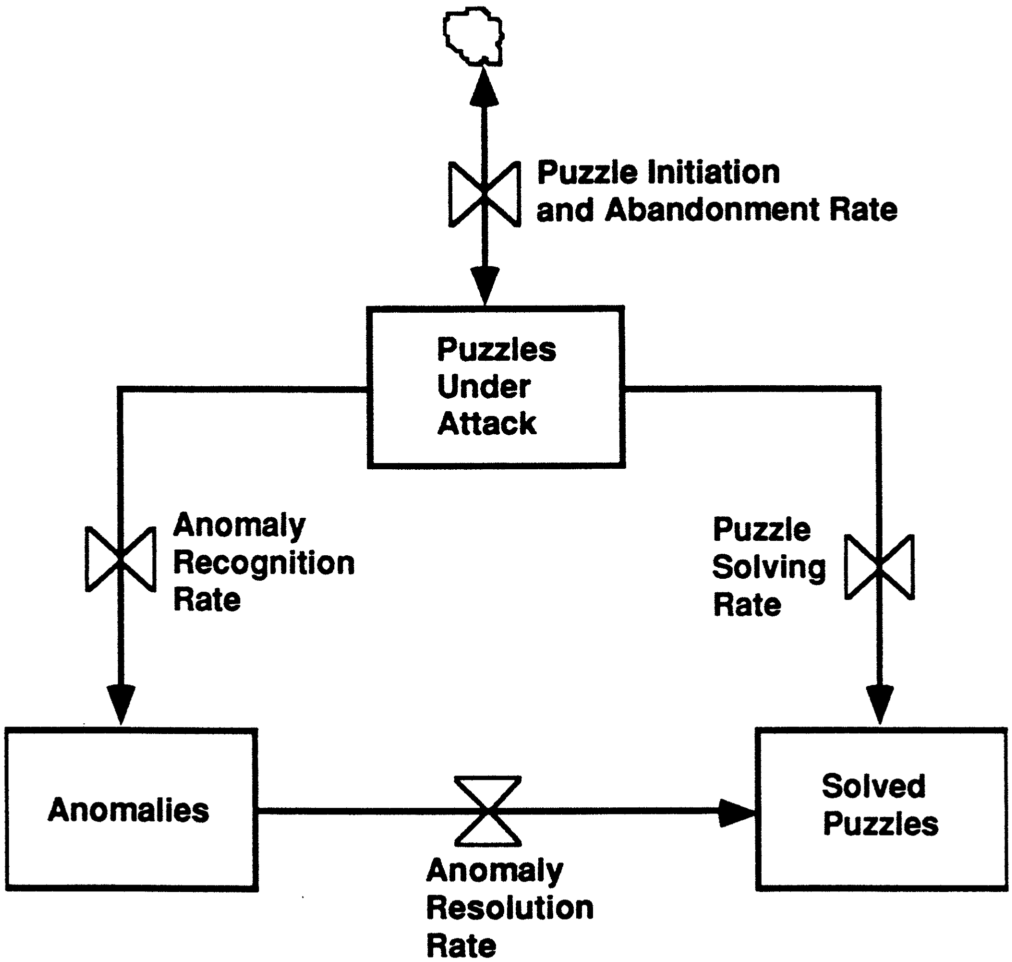

Figure 4

Determinants of the Puzzle-Solving Rate

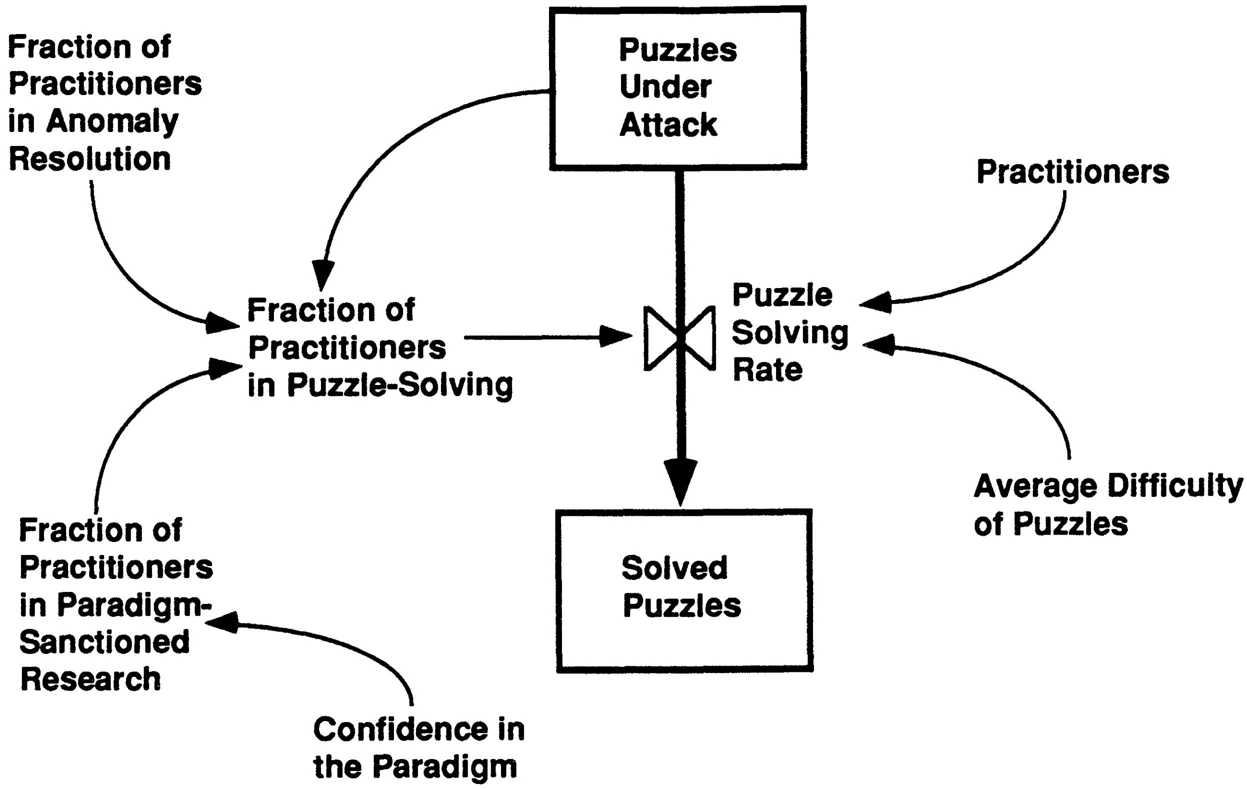

Figure 5

Determinants of the Anomaly Resolution Rate

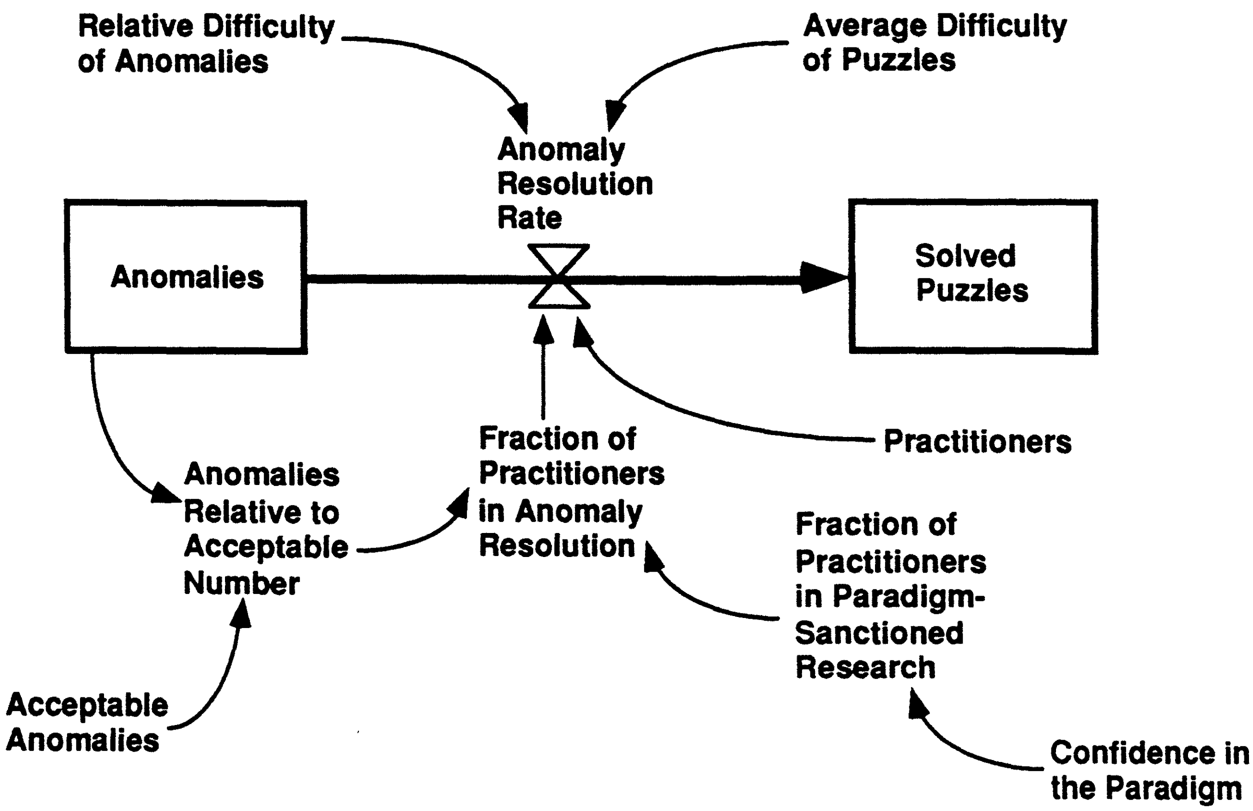

Figure 6

Internal and External Determinants of the Recruitment and Defection of Practitioners

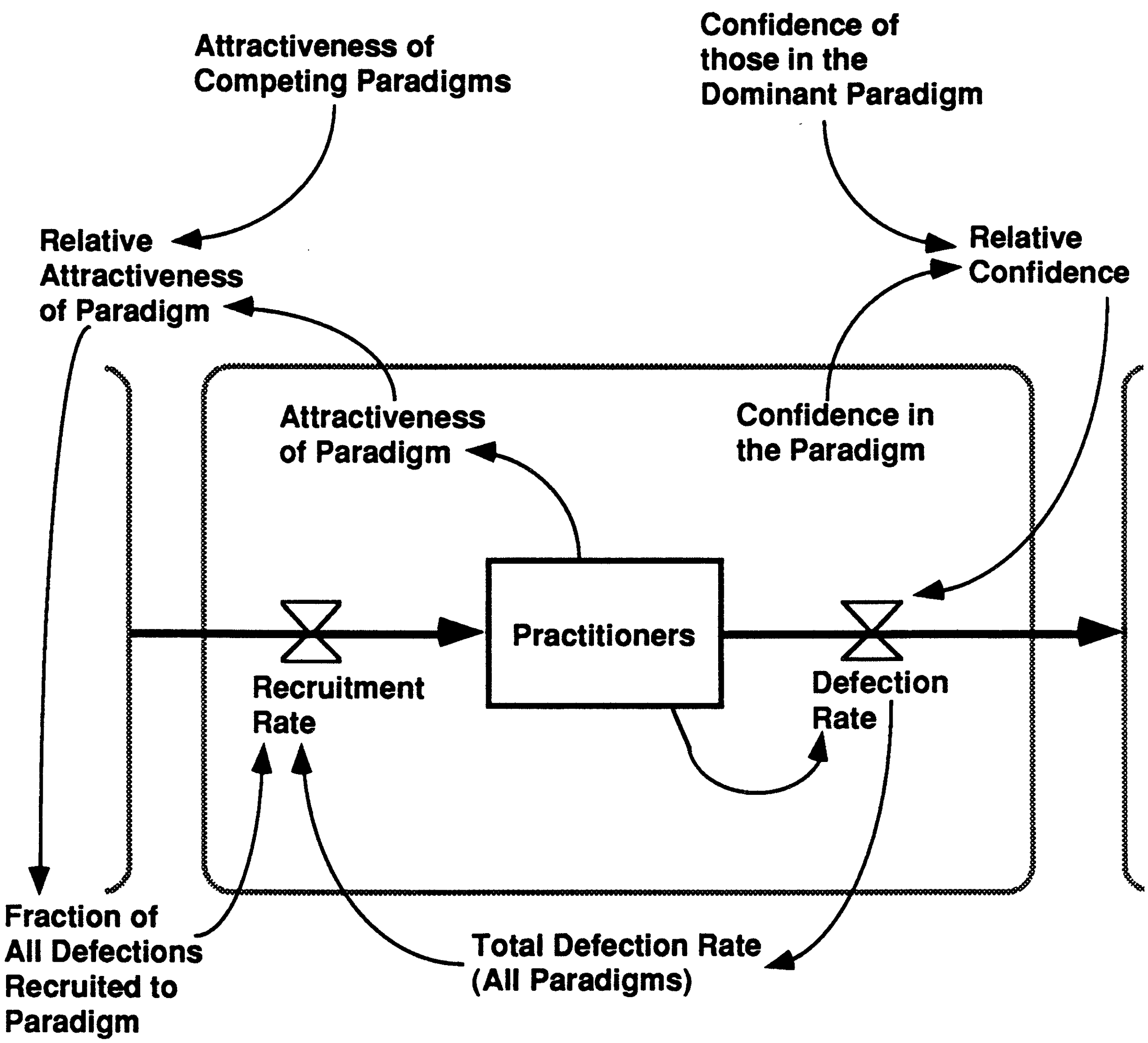

Figure 7

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 7a

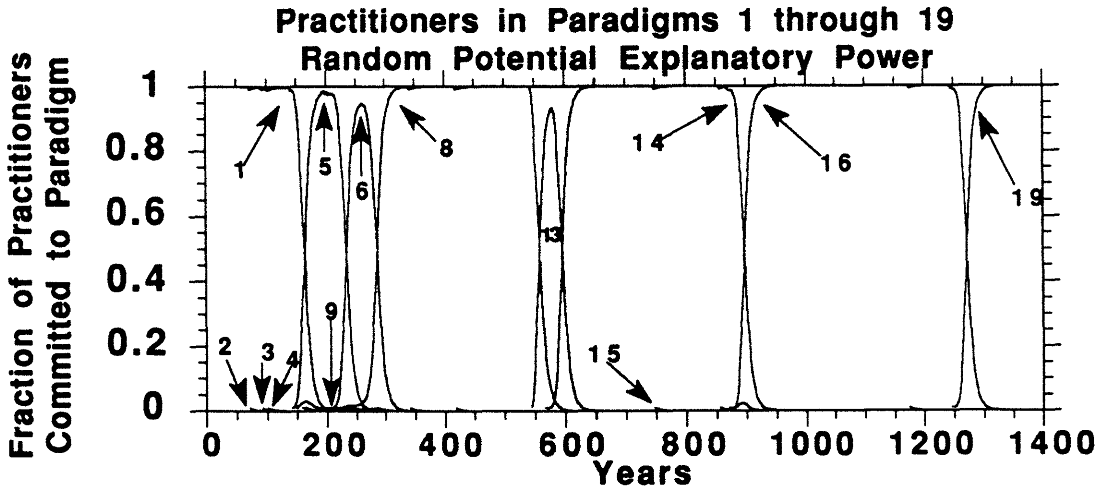

Figure 7b

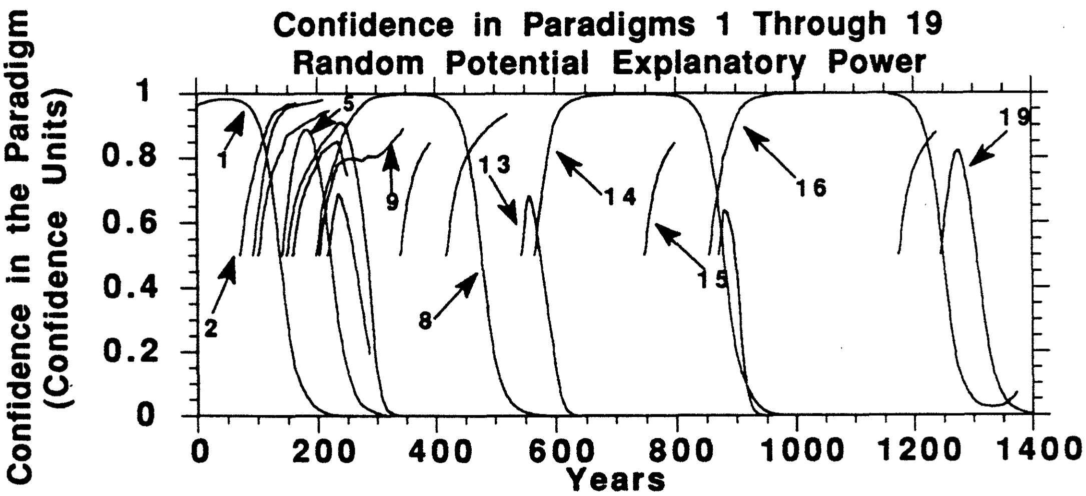

Figure 8

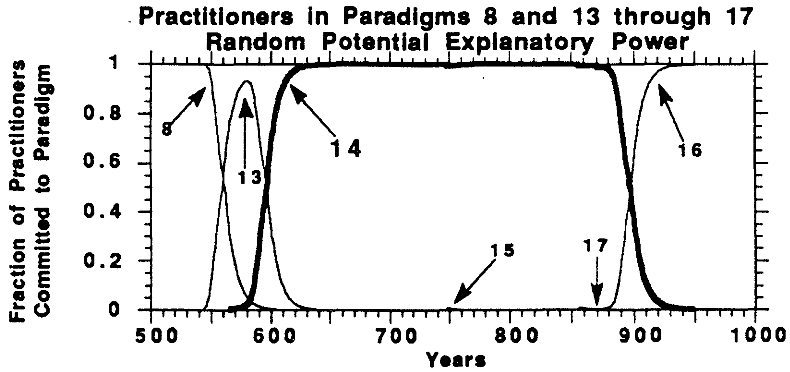

Figure 9

The Lifecycle of Paradigm 14

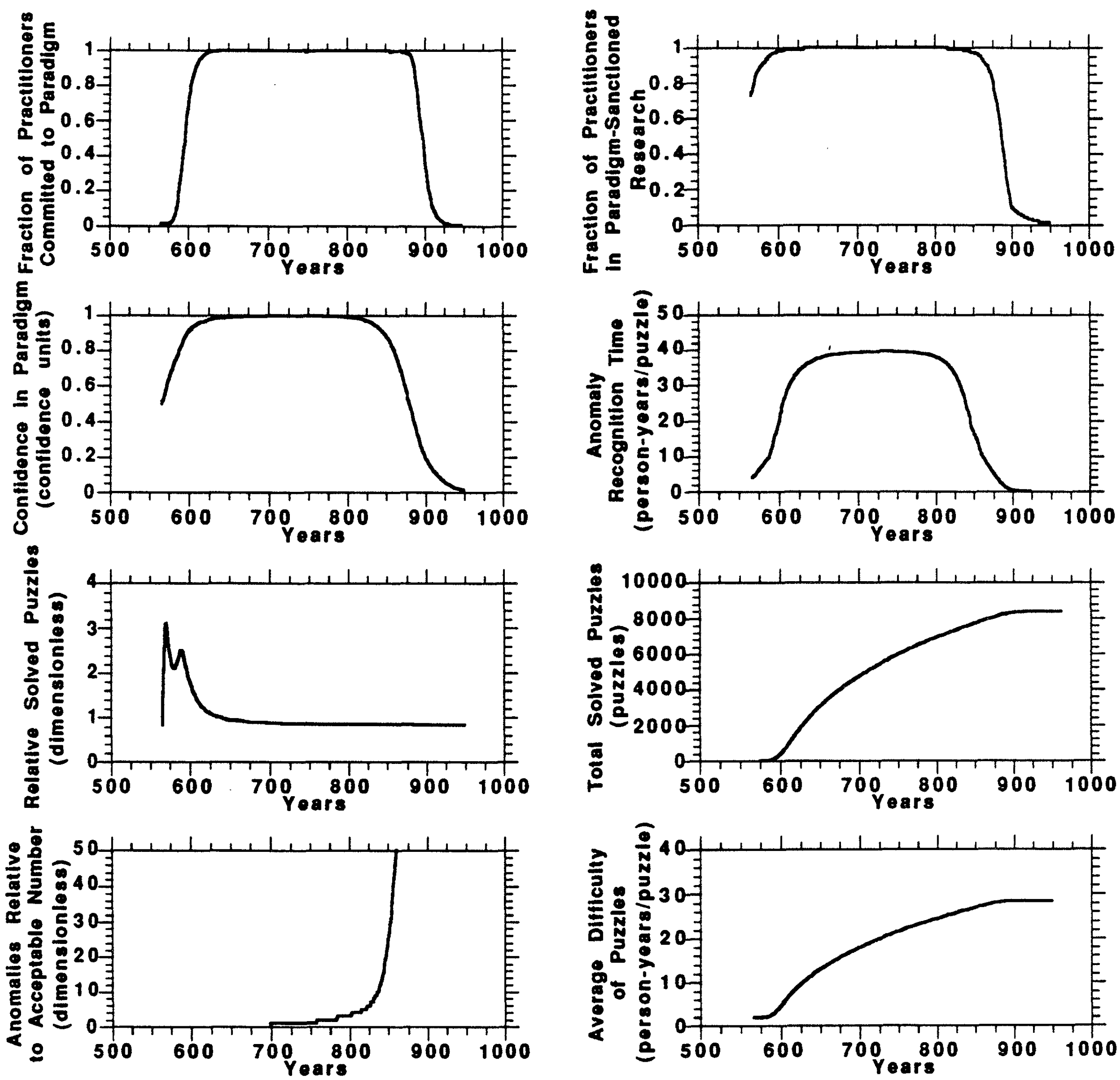

Figure 10

Two feedback loops that cause initially uncommitted and unorganized practitioners to coalesce into a highly focused paradigm.

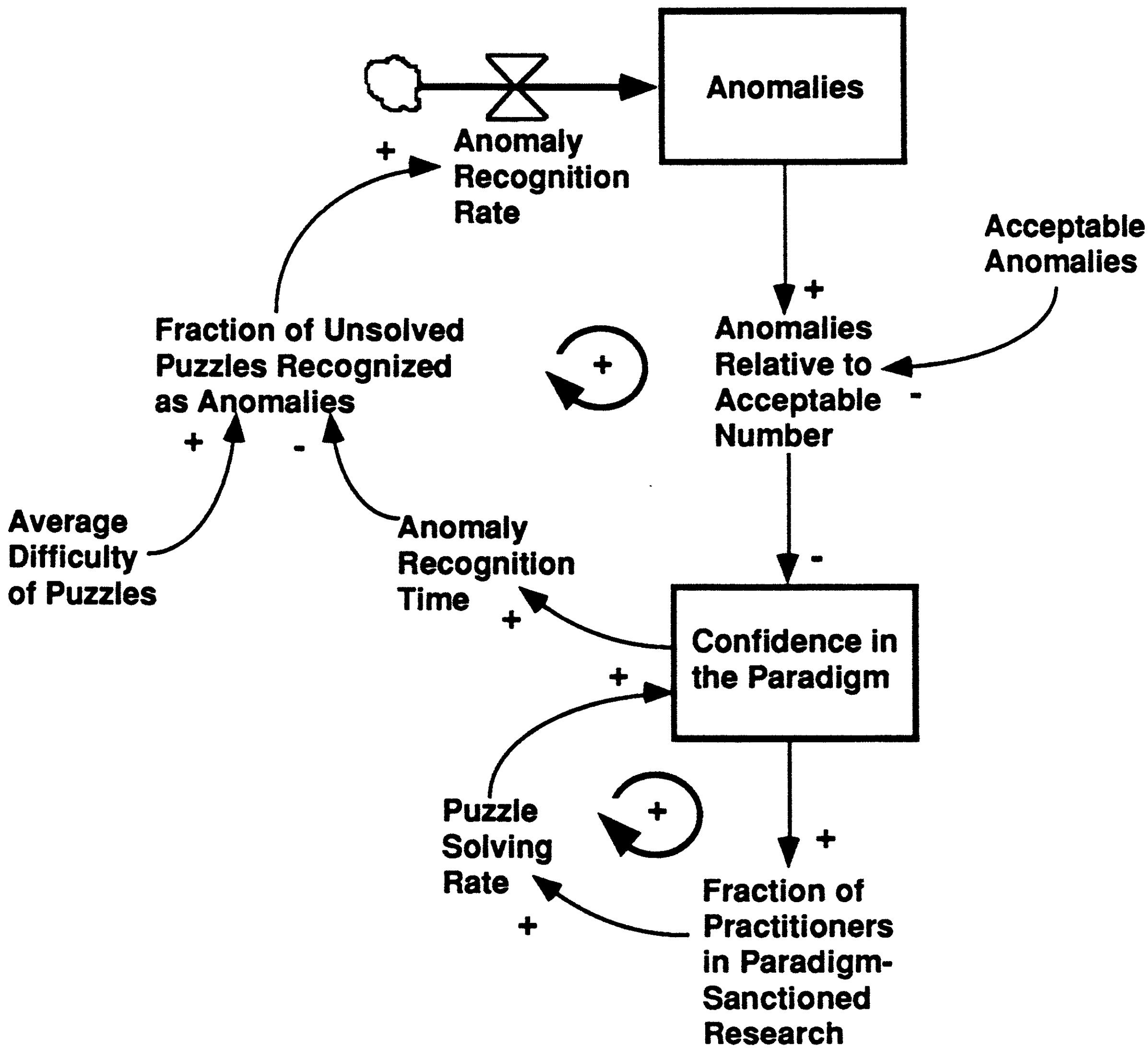

Figure 11

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.

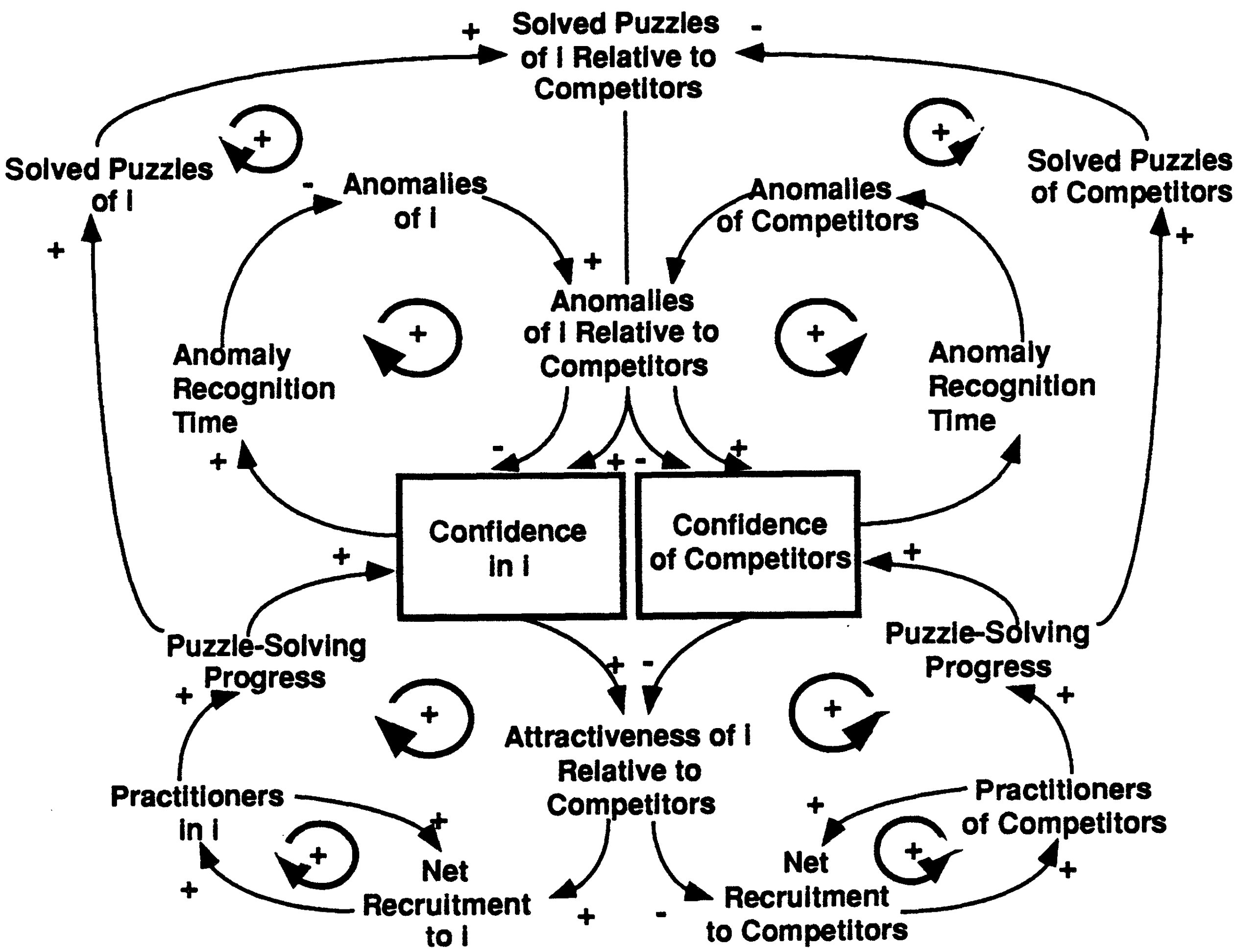

Table 1

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.

Indep Variable	Estimated Coeff	Standard Error	t-statistic
Constant	5.44	0.52	10.42*
C	6.86e-4	4.34e-4	1.58
C^{pdom}	-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 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.

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

$\lambda_b = 0.51$

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.

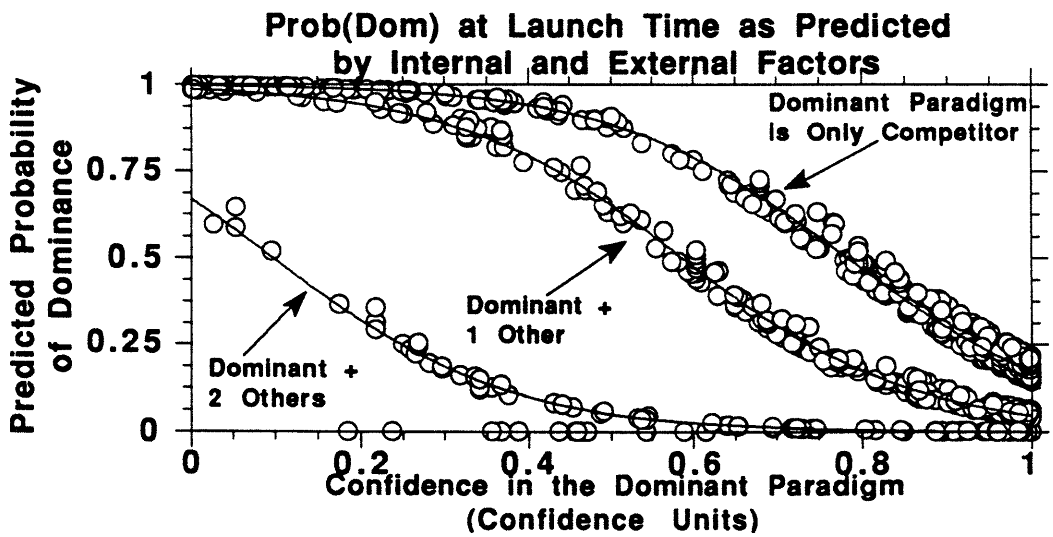

Figure 13

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.