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Testing a Theory of Scientific Revolutions With a Formal Model

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ABSTRACT

Modern theories of science emphasize scientific revolutions rather than the traditional cumulative view of scientific progress. Thomas Kuhn, in particular, has formulated a theory of science based on the lifecycle of paradigms. Though Kuhn's theory is attractive, no calculus is offered by which the theory can be tested. This study tests the dynamic consistency of Kuhn's theory by formalizing the theory and testing it with a computer simulation model. The model plays the roles of the actors, tracing out the consequences of their day-to-day actions. Sensitivity tests are used to explore the importance of various hypotheses. Results show the theory to be dynamically consistent: the lifecycle of paradigms described by Kuhn can be accounted for by Kuhn's theory. Kuhn's theory thus passes a test to which few other theories of science have been subjected. The study shows how modeling can provide a method for testing theories even when those theories are stated entirely in qualitative terms, at a high level of abstraction, and in a context divorced from explicit dynamic analysis.

THE GROWTH OF KNOWLEDGE:
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> ...it is the customary fate of new truths to begin as heresies and end as superstitions....
>
> Huxley [1]

A New View of Science

Recent years have witnessed a dramatic upheaval in the philosophy of science. The old notion that science is a logical, rational enterprise continually adding to the stockpile of knowledge has been challenged; many now recognize that the evolution of science is punctuated by violent disruptions.[1] During such crises, or scientific revolutions, a tried and true theory is abandoned for an untested and often heretical alternative. Rather than building upon the old theory, the new theory destroys the old. Though the successor may flourish for centuries, eventually another crisis develops and another revolution occurs. Some even claim science is completely anarchic, more a no-holds-barred brawl than a calm, reasoned investigation of reality.[2]

Yet the new view of science does not mean it is random. Indeed, the proponents of the new view, notably Thomas Kuhn in his Structure of Scientific Revolutions [7], argue that scientific development is shaped and guided by an internal logic and structure. Forced to reject the traditional cumulative view of scientific progress through historical analysis, Kuhn identifies a recurrent pattern of scientific development culminating in revolution. To explain the pattern of dynamics he establishes, Kuhn proposes a theory rooted in the day-to-day practice of science. Kuhn's theory constitutes a dynamic hypothesis of scientific revolutions, that is, it consists of causal hypotheses about the way scientists actually work, which, Kuhn asserts, interact with nature and society to produce the dynamic pattern of scientific revolutions. Kuhn's emphasis on the uncertain, messy, and personal character of actual scientific endeavor lends his theory great appeal. Yet, even if one accepts the dynamic hypothesis, Kuhn offers no method to check whether or not the theory he proposes can actually produce the behavior he seeks to explain. In the absence of a calculus to deduce the consequences of Kuhn's assumptions, the chief arena for debate over the theory has been historical interpretation and philosophical analysis.[3]

The purpose of this paper is to test the dynamic consistency of Kuhn's theory in another manner, by formalizing it and then testing the formalized theory with a computer simulation model. Like Kuhn's work, the model constitutes a theory of scientific revolutions, and consists of hypotheses about the ordinary business of doing science. The purpose of the model is simply to play the roles of the actors in the system and trace out the consequences of their actions over time, thus providing a test of the theory by checking whether the assumptions can actually produce the lifecycle of scientific revolutions.[4]

Defining the Problem

The classic examples of scientific revolution are the Copernican and relativistic/quantum revolutions. It is widely recognized that these events signalled profound shifts in human understanding of nature. At the same time, revolutions were thought to be rare, marking the transition from superstition to science, from myth to method. But the history of science does not sit well with this view. Kuhn points out the dilemma facing historians of science:

> The more carefully they study, say, Aristotelian dynamics, phlogistic chemistry, or caloric thermo-dynamics, the more certain they feel that those once current views of nature were, as a whole, neither less scientific nor more the product of human idiosyncracy than those current today. If these out-of-date beliefs are to be called myths, then myths can be produced by the same sorts of methods and held for

> the same sorts of reasons that now lead to scientific knowledge. If, on the other hand, they are to be called science, then science has included bodies of belief quite incompatible with the ones we hold today. [10]

Kuhn resolves the dilemma by recognizing the scientific revolution as a basic feature of science. He argues that new theories tend to replace old ones rather than building upon them. New theories are usually incompatible with the old, built on different metaphysical foundations, relying on different observations, research methods, and criteria for validity. These and other characteristics of a scientific school define what Kuhn calls a paradigm. The concept of paradigms is central to Kuhn's analysis. It is rich in meaning and nuance, and several key senses need to be distinguished.[5]

> Paradigms are specific works that define a field. They are accepted examples of actual scientific practice--examples which include law, theory, application, and instrumentation together--[they] provide models from which spring particular coherent traditions of scientific research. [12]

Thus Newton's Principia and Keynes's General Theory are paradigms.

Paradigms define the nature of a particular science. They provide the tools, methods, and examples that guide practitioners in their research:

> Close historical investigation of a given specialty at a given time discloses a set of recurrent and quasi-standard illustrations of various theories in their conceptual, observational, and instrumental applications. These are the community's paradigms, revealed in its textbooks, lectures, and laboratory exercises. By studying them and by practicing with them, the members of the corresponding community learn their trade. [13]

The history of science is the history of the rise and fall of such communities. The great diversity of these cultures, from phlogistic chemistry to neoclassical economics, suggests the forces behind the growth and decline are independent of the particular beliefs, people, and methods that make them up. A credible theory should identify a set of generic forces, the underlying structure responsible for the pattern of behavior common to all paradigms.

But what exactly is this common pattern of behavior? One element has already been identified: the growth and decline in membership. A new paradigm emerges with the work of a single, or at most several, persons. If successful, the paradigm attracts practitioners away from other schools. Growth ceases when nearly all the practitioners in a given field embrace the paradigm, for example, when 'physicist' came to mean 'Newtonian'. Dominance may be long- or short-lived. Eventually, however, the paradigm starts to fail (in a special sense discussed below) and loses members to new theories. Often recruitment ceases as young scientists are drawn into a competing school and the paradigm simply dies away.

The character of scientific activity also changes over the lifecycle of growth and decline. New paradigms are largely untested--often the proper way to apply a theory is unclear at first even to its creators. The result is conflict over the fundamentals and disagreements over the facts, slowing progress. When one paradigm gains the upper hand, however, the character of research changes rapidly. Kuhn recounts the history of electrical research to illustrate the process.[6] At first, there was no guiding paradigm and confusion reigned. No one could agree on which facts were important or even what the facts were. After years of conflict, Franklin proposed a theory that "could account...for very nearly all [the known electrical] effects and that therefore could and did provide a subsequent generation of 'electricians' with a common paradigm for its research." [14] The result was dramatic:

> Freed from concern with any and all electrical phenomena, the united group of electricians could pursue selected phenomena in far more detail, designing much special equipment for the task and employing it more stubbornly and systematically than electricians had ever done before. Both fact collection and theory articulation became highly directed activities. [15]

Conflict and confusion gave way to purposeful, efficient activity. Kuhn calls such activity normal science.

Normal science is puzzle solving. It is the extension and exploration of a paradigm. The dynamic feature of interest is the cumulative nature of puzzle solving within a given paradigm. Scientists try to build upon the foundation the paradigm work laid out and force nature into line with a paradigm, not elicit new and unusual phenomena from her. But new and unusual phenomena do arise. As normal science progresses, results are obtained that do not fit into the range of expectations determined by the paradigm. Kuhn terms such novelties anomalies. Anomalies are not simply disagreements between fact and theory, for these occur constantly. Indeed, one of the tasks of normal science is to bring fact and theory into ever closer agreement (and often this is accomplished more by adjusting the facts than by refining the theory).[7]

The null result of the Michelson-Morley experiment is a particularly famous example of anomaly. Other examples from Newtonian physics include the photoelectric effect and ultra-violet catastrophe; modern physics is plagued with 'renormalization' and the seemingly never-ending growth in the ranks of the 'elementary' particles. Again, the dynamic feature of interest is that the progress of normal science, an activity whose aim is to suppress novelty, produces anomalies that begin to accumulate. When the level of anomalies reaches a certain point, the character of research changes again, entering a phase Kuhn calls crisis.

Crisis develops when scientists begin to lose faith in the paradigm. Under normal science, the paradigm has priority--in a clash between reality and expectation, the burden of proof is on reality. But as anomalies accumulate, that burden slowly shifts onto the paradigm. Coming to question their tools and methods, and unwilling to trust their paradigm-conditioned intuition, scientists find themselves adrift in an ocean of confusion. Research is diluted as practitioners increasingly abandon puzzle solving to take up the anomalies. Some even "desert science because of their inability to tolerate crisis." [16] New theories and ad-hoc patches to the old theories are proposed. The situation is much like that in electrical research before the emergence of Franklin's theory. Crisis persists until a theory emerges that can attract enough followers and explain enough of the anomalies to become the next paradigm. The transition is the scientific revolution.

Four stages in the lifecycle of a paradigm have been described: emergence, normal science, crisis, and revolution. The basic pattern is fundamental, though there are differences in timing and severity peculiar to each case. The entire process may take a few years or a few centuries; a new paradigm may appear rapidly or crisis may deepen for decades. Figure 1 is a generic representation of the basic pattern. It is the reference mode, the behavior that a theory of scientific revolutions must generate. To be credible, a theory must produce the reference mode without relying on external driving forces such as the emergence, as if by magic, of a new and better theory. Further, the theory should be a plausible representation of the way scientists actually work. The triple requirements of reproducing the reference mode internally with a plausible behavioral structure are strong constraints. But satisfying them is by no means sufficient to prove the theory. Indeed, proof is the wrong dimension for evaluation. Rather, the goal is to illuminate the dynamics of scientific revolutions by making explicit the connections between the ordinary business of scientific research and the dramatic changes in our conception of the world that come out of it.

A Model of Scientific Revolutions

The Paradigm as Metaphor

The heart of the theory presented here is the identification of the metaphysical and epistemological facets of paradigms with metaphors. In essence, the dynamic hypothesis is that paradigms are metaphors, and metaphors are limited representations of reality that crack when strained, producing anomaly and crisis. Four properties of metaphor in particular bear elaboration.

1. Metaphor is everywhere: I.A. Richards notes, "we cannot get through three sentences of ordinary fluid discourse without it. [17] Nelson Goodman echoes Richards by saying, "metaphor permeates all discourse, ordinary and special, and we should have a hard time finding a purely literal paragraph anywhere." [18] C.M. Turbayne goes farther by emphasizing that metaphor permeates all of our thought as well as our language. [19] Similarly, Kuhn stresses the priority of paradigms, speaks of analogies as the foundations of paradigms, and suspects that "something like a paradigm is prerequisite to perception itself." [20]

2. Metaphor involves a "transfer of schema" from one area of experience to another:[8] 'Metaphor' means 'to carry across'. Consider the metaphors 'Richard is a lion', 'the brain is a computer', or 'capitalist economies are markets.' The characteristics of lions, computers, and markets are transferred, via the metaphors, to Richard, the brain, and capitalist economies. The metaphors work because the characteristics of lions, computers, and markets are well known and carry a constellation of meanings, examples, connotations, and nuances that illuminate the subjects to which they are applied. Max Black calls this constellation a "system of associated commonplaces." [21] Both ancient and modern scientific theories are grounded in

metaphors drawn from common experience: consider Heraclitus's 'all is fire', the wave model of light, and the plum-pudding model of the atom.

3. Metaphors filter reality: The image of the filter appears constantly in discussions of metaphor, and is itself a crucial metaphor. Because a metaphor draws upon a system of associated commonplaces, certain relationships are highlighted while others are suppressed. Black's image is a piece of smoked glass. Looking at the night sky through such a glass blocks out some stars, thereby accentuating others. Stars that were not noticed before can also be seen. The filtering power of paradigms is central to Kuhn's theory as well: "In the absence of a paradigm...all of the facts that could possibly pertain to the develcpment of a given science are likely to seem equally relevant." [22] It is interesting that the images used to describe the operation of metaphor are so similar. Black uses smoked glass, Turbayne uses the emerald goggles of Oz, and Kuhn mentions glasses that turn the image of the world upside down:

> ...the scientist who embraces a new paradigm is like the man wearing inverting lenses. Confronting the same constellation of objects as before and knowing that he does so, he nevertheless finds them transformed through and through in many of their details. [23]

The filtering aspect of metaphor is often expressed by saying metaphors are models of reality.[9]

4. Metaphors define reality: In addition to organizing perception through the transfer of schema, metaphor creates the world, or at least a part of the world. Black notes:

> It 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 antecedently existing. [24]

Turbayne argues for the power of metaphor to shape the world with the history of Cartesian mechanism, concluding:

> ...enthralled by his own metaphor, [Descartes] mistook the mask for the face, and consequently bequeathed to posterity more than a world view. He bequeathed a world....Had he [chosen a different metaphor]...we should now be living in a different world. [25]

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. [26]

Parallels between metaphors and paradigms could be extended indefinitely but the point is clear. The term 'metaphor' or 'extended metaphor' can be substituted for the term 'paradigm' without doing violence to the sense of either one.

Science, then, can be viewed as the elaboration and exploration of metaphors. More precisely, normal science is the elaboration of metaphors. The formulation of a theory corresponds to the initial transfer, and the exploration of the metaphor to what Kuhn calls the articulation of the paradigm.

Though a metaphor is usually inspired by a small number of similarities, other connections are soon noticed. When first formulated, not all the connections are apparent. The metaphor is unexplored. Indeed, the attraction and power of metaphor lies in its ability to suggest undreamt-of possibilities that open the door to elegant or useful visions of reality. The task of normal science is to search out these possibilities and build upon them just as a poet constructs an image and carefully draws out the crosscurrents.

Fresh metaphors jangle and startle; they are impudent and lively, setting the mind off in new directions and creating new insights into familiar problems. With usage comes familiarity, and familiarity breeds contempt; soon its filtering nature is forgotten. Metaphors _qua_ metaphors are mortal, for "with repetition, a transferred application of a schema becomes routine, and no longer requires or makes any allusion to its original referent. What was novel becomes commonplace, its past is forgotten, and metaphor fades to mere truth." [27] Similarly, newly proposed theories are often introduced explicitly as models or metaphors. Kuhn cites Copernican astronomy which was introduced as a convenient fiction, that is, it was convenient to treat the solar system as if the earth travelled around the sun. Only later, as scientists gained confidence in the theory did heliocentrism become accepted, the convenient fiction transformed into scientific truth.[10] Even today, nearly seventy years after the introduction of general relativity, the vast majority of people unequivocally believe in the truth of the Copernican system.

While metaphors that become commonplace live on as truth, not all metaphors are so lucky. Metaphors are inherently limited, and if pushed too hard will strain and crack. To consider a simple example, suppose 'man is a wolf' is proposed as a theory of human nature. Should it become the accepted paradigm, the task of normal science would be to extract useful insights from the metaphor. Statements such as 'man is fierce and engaged in constant struggle', 'men travel in packs', and 'men have accepted leaders' might result. Such statements could be illuminating and even contribute to the design of governments, law, and technology. At some point, however, further application of the metaphor would begin to yield statements like 'man has fur and big teeth', and 'man has eyes, ears, and a nose'. Such statements either blatantly clash with experience or are trite. They are anomalies. They arise from the fabric of the theory itself through the normal application of puzzle solving. The accumulation of anomalies undermines the utility and appeal of metaphors and can send them to the grave, disgraced as falsehood.[11]

The Structure of Puzzle-Solving

Capturing the complex and subtle processes of metaphor birth, exploration, and death in a simulation model involves many simplifications. The model shold be viewed more as a rough translation of the theory into formal terms than as a definitive rendering. The major sectors of the model are shown in Figure 2. 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 being attacked, but which have not yet yielded or been recognized as anomalies. Four flows connect the different categories. Under normal conditions, puzzles are formulated and brought under attack as others are solved. Under conditions of collapse, however, there may be too many puzzles under attack for the number of practitioners remaining, and the abandonment of puzzles will dominate. If all goes well, a puzzle, once formulated and attacked, will be solved in fairly short order. Such puzzles flow into the class of solved puzzles via the puzzle-solving rate. If the puzzle is recalcitrant, however, it can become recognized as an anomaly. Anomalies can sometimes be resolved into solved puzzles. The shifting balance between these flows determines the behavior of the system, and thus the forces affecting them are crucial.

The determinants of the initiation and abandonment rate are straightforward. The number of practitioners involved in puzzle solving defines a desired level of puzzles under attack, corresponding to the normal volume of research in the field. When the actual number differs from the desired level, research is initiated or abandoned to make up the difference. The number of puzzles solved each year depends on the number under study, the fraction of practitioners involved in sanctioned research and of those the number involved in puzzle solving, and the average difficulty of puzzles (Figure 4). Practitioners within a paradigm can be involved in different types of work. The majority will usually be involved in puzzle solving, while some will be working to resolve anomalies, and others, dissatisfied with the paradigm but unable or unwilling to defect to another, try to come up with alternatives, write philosophical essays, etc. Those involved in puzzle solving and anomaly resolution make up the fraction of practitioners in paradigm-sanctioned research, a function of the degree of confidence practitioners have in the paradigm. When confidence is high, almost everyone is involved in sanctioned research. If confidence drops, however, the number in sanctioned research drops as practitioners lose faith in the paradigm.

Confidence is (arbitrarily) defined on a scale from zero to one. A confidence level of one corresponds to absolute certainty in the truth of the paradigm. It implies that the practitioners have so much faith in the paradigm no experience could challenge it; no observation or result could convince them the paradigm was not true. Similarly, a confidence level of zero implies absolute certainty the paradigm is false. No experience could convince them it had anything to offer. The midway point is neutral, where practitioners are neither leaning toward the paradigm or away from it; it is the point of maximum doubt.

The most important determinant of the puzzle-solving rate, however, is the average difficulty of puzzles. It is assumed that, on average, puzzles become more difficult to solve as the number of solved puzzles grows. The relationship between solved puzzles and difficulty captures the notion that a metaphor gets harder and harder to explore as it is elaborated and developed. It is the core of the dynamic hypothesis. There are several ways the 'depletion' of metaphors could have been represented. One way would be to assume that a finite number of puzzles fall in the domain of the paradigm; when these are exhausted, further work produces nothing but anomalies. Masterman advocates such a view:

> ...it is not only the case that a fully-extended paradigm, or theory, reaches a point where further extension of it produces diminishing returns. The situation is worse. The paradigm itself goes bad on you, if it is stretched too far, producing conceptual inconsistency, absurdity, misexpectation, disorder, complexity, and confusion, in exactly the same way as a crude analogy does, if pursued too far, say, in a poem.... The property of crudeness...[means] that a paradigm must be finite in extensibility. [30]

While Masterman's hypothesis is sufficient to cause paradigms to collapse (in the same way that the extraction of all the oil from a well is certain to shut it down), it is not necessary. Indeed, the notion that paradigms are finite is an extremely strong assumption. In contrast, it is assumed here that the puzzle-solving potential of a paradigm is infinite, but as normal science progresses, puzzles gradually become more difficult to solve. The growth in difficulty is gradual because practitioners attack the easy puzzles first, leaving the difficult ones for advances in technology or theory. Often advances in technique and theory are required before more dirfficult puzzles can even be formulated or recognized. In addition, successful paradigms get applied in realms quite far from their original field just as Newtonian mechanics, a theory formulated to deal with terrestial and celestial motion, came to be applied to subatomic phenomena. The farther from home the metaphor is applied, the more likely nature is to step outside the boundaries it establishes.

The forces determining anomaly resolution are similar to those affecting puzzle solving. The rate at which anomalies are resolved into the theory 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 relatively more difficult to solve than puzzles, and as the difficulty of puzzles increases, the difficulty of anomalies rises proportionately. The fraction of practitioners involved in anomaly resolution depends on the balance between the number of anomalies and the acceptable number. The acceptable level of anomalies is the number that can be tolerated without losing confidence in the paradigm. The acceptable level is not zero, for some problems always face any theory, and to lose confidence the first time an anomaly crops up would be to abandon a theory that may have a great deal to offer. If the number of anomalies increases, scientists are drawn into anomaly resolution; if they are successful the number of anomalies stabilizes or declines. Kuhn notes that practitioners are extremely reluctant to work on anomalies. Except for a few scientists who thrive on tension and confusion, the vast majority prefer the relative safety and professional rewards of puzzle solving.

Recognizing a puzzle as an anomaly requires a complex judgment. Anomalies are not simply experiments that run counter to expectation. There are always disagreements between fact and theory; it is the task of normal science to reconcile the two. Only when normal science repeatedly fails to resolve the differences or explain some novelty does a puzzle become recognized as an anomaly. Thus, in contrast to the theory that there are 'crucial experiments' that provide potential falsifications of a theory, the view adopted here is that there is no fundamental difference between an ordinary unsolved puzzle and an anomaly except the length of time it has resisted solution.[12]

The longer a puzzle resists solution, the more likely it will be recognized as an anomaly. Thus, the fraction of puzzles recognized as anomalies depends on the balance between the average time required to recognize an anomaly and the average time required to solve a puzzle. When the recognition time is high relative to the average puzzle-solving time, few anomalies will appear since few will remain unsolved for the length of time required to become an anomaly. When the recognition time is low relative to the average puzzle solving time, most of the puzzles under study will be considered anomalous before they are solved.

Anomaly recognition depends critically upon the practitioner's confidence in the paradigm. If practitioners believe the paradigm is 'true', they are more reluctant to recognize anomalies than if they are not as confident, in the same way that the freshly-minted metaphor is obviously only a metaphor but the old one is taken uncritically to be literal truth. It is not simply a matter of knowing the paradigm is wrong and refusing to admit it.. When practitioners are highly confident of a paradigm their perceptions are so conditioned by it that they cannot recognize or assimilate phenomena that violate it.[13]

The Role of Confidence

Confidence is the focal point of the model. Confidence influences the way practitioners allocate their research effort, how they perceive anomalies, and determines recruitment and defections into and out of the paradigm. Confidence represents a constellation of attitudes and commitments. It reflects basic beliefs about reality by capturing the extent to which practitioners take the metaphor defining a paradigm as literal truth. In the model, confidence responds to the progress of normal science and to the number of anomalies, and thus is a measure of the health and vigor of a paradigm. (Figure 6). Confidence tends to decline when anomalies exceed their acceptable level and rises when they are below it. Confidence also declines when the rate of progress of normal science falls below a goal defined by the historical number of solved puzzles modified by the expected growth of solved puzzles.

The impact of progress and anomalies on confidence depends on the degree of confidence itself. When confidence is very high or very low, practitioners are relatively unwilling to change their attitudes. At the extremes, where practitioners are absolutely certain that the paradigm is true (or false), confidence cannot change at all, by definition. In the midrange, where uncertainty and doubt dominate, confidence can change fairly rapidly since practitioners have no strong reasons for accepting or rejecting the paradigm.

The Paradigm as Community: Recruitment and Defection

At any moment in the life of a paradigm there is a group of practitioners committed to it comprising some fraction of the membership in the field. In reality, commitment is a grey area: there are degrees of training and familiarity, there are pure researchers and pure teachers, philosophers and technicians, and all combinations in between. These distinctions are lumped together here. A practitioner is considered committed to the paradigm if the paradigm is the person's primary guide to professional. reality. Membership grows through recruitment and shrinks through defections; the determinants of these flows are therefore the determinants of the rise and fall of paradigms. In reality, many forces influence recruitment and defection such as demonstrated puzzle-solving ability, the presence of anomalies, the strength of alternative theories, state attitudes toward science, the availability of funding, etc. In the model, practitioners are assumed to respond to the confidence of those in the paradigm relative to the confidence of outsiders in alternative paradigms (Figure 7). Confidence represents accumulated puzzle-solving ability and the threat from anomalies; it is used to proxy funding and attitudes. When the paradigm is more attractive than its competitors, recruitment exceeds defections. If confidence falters, membership declines as defections exceed recruitment.

The confidence of practitioners belonging to alternate paradigms is assumed to be constant, corresponding to the assumption that there is always a competing paradigm available and that it has an unchanging degree of confidence. While clearly not true, this assumption is justified for several reasons. Competing theories do not arise at random. They tend to be born in the crisis phase of an existing paradigm, and are scarcer during the period of normal science. They are part and parcel of the dynamic process. Thus, in the emergence phase of a new paradigm, recruitment would be easier than assumed here, since the old paradigm would be in crisis and confidence would be low. During normal science, alternatives would die away, and thus defections in the early phases of the crisis would be retarded, trapping the disgruntled practitioners in the dying paradigm. The ease of recruitment and the willingness of practitioners to defect depends on the fraction of the total number of practitioners committed to the paradigm. Recruitment gets more difficult as membership approaches 100% since the most willing practitioners will be recruited first, leaving those who are either strongly committed to alternative paradigms or simply unable to make the shift. A symmetrical relationship affects defections, reducing the willingness of remaining practitioners to defect as the number of practitioners declines.

Data Limitations

There are no numerical data available on paradigms, no standard time series for puzzles, anomalies, or confidence. There is, however, a rich store of qualitative data, impressions, common sense, and historical episode and anecdote. These, along with theories of metaphor and science, form the basis for the model. But computers demand numbers, and the model does contain precisely quantified relationships. Obviously the numbers chosen are highly conjectural. Fortunately, the precise numbers do not seem to matter to the overall behavior of the model. Changing parameters does, as will be seen in the next section, change the timing of events and the particular values variables take on, but the fundamental behavior of the system is invariant to such changes. Thus the great uncertainty surrounding numerical values does not constrain the use of formal modeling as a theory testing tool.

Testing the Theory

Figure 8 shows the reference run of the model. The overall length of the lifecycle depends on the parameters of the model, particularly the inherent explanatory power of the paradigm. To distinguish the different phases of the lifecycle, the reference run corresponds to a strong paradigm such as Newtonian physics. Thus, the simulation spans three hundred years, a rather long lifetime for a paradigm.

The initial conditions represent a newly-emerged theory. There are few practitioners, they have solved few puzzles, and there are no anomalies since the theory is so young and the metaphor virtually unexplored. The practitioners' initial degree of confidence is one-half, meaning they are in doubt about the validity of the paradigm, neither leaning toward it or away from it.

In the first three decades of the simulation, there is a dramatic increase in confidence. Confidence rises because anomalies are low relative to the acceptable level and because there is a large surge of progress in puzzle solving. Confidence is not simply responding to these pressures, however. Progress is high and anomalies are low because confidence is rising. Rising confidence creates the pressures that cause it to grow. Several self-reinforcing feedback mechanisms are responsible for the rise in confidence.

Rising confidence boosts progress. Initially, only three quarters of the practitioners' time is spent in paradigm-sanctioned research. The paradigm is so new and shaky practitioners must spend much of their time interpreting their results from the new vantage the paradigm affords, just as the early quantum physicists spent years trying to understand the implications of the uncertainty principle. As confidence begins to rise the doubts and confusion of the practitioners wane, and more are drawn into sanctioned research. Progress rises, and with it upward pressure on confidence. An increase in confidence is a natural reaction to a new theory that can solve some problems, shows promise of solving many more, and has no serious strikes against it yet, even though it is largely unfamiliar. The effect of this positive feedback process (Figure 9) is to create a burst of progress in the paradigm's early years, a flush of early success that spurs interest in the theory. The process saturates when the vast majority of practitioners are involved in sanctioned research.

Confidence continues to rise rapidly even after progress slows. Progress is still greater than expected, exerting some upward pressure, but most of the impetus causing confidence to grow comes from the low relative number of anomalies. Anomalies are held down by the growth in confidence itself (Figure 10). Rising confidence increases the anomaly recognition time as practitioners, increasingly familiar with and certain of the paradigm, begin to see reality through paradigm-conditioned eyes. The result is to suppress the appearance of anomalies even though the average difficulty of puzzles is increasing. In turn, the small number of anomalies boosts confidence even more.

At the end of the emergence phase practitioners are growing, confidence is still rising, and solved puzzles are growing slightly. In the next four decades, the paradigm grows from about ten percent of the total community to virtually one hundred percent. Again, there are self-reinforcing processes at work. As the number of practitioners grows, the number of students they teach, articles they publish, conferences they attend, and societies they belong to increases, further increasing the number of practitioners. A bandwagon effect develops. At the same time, as the number of practitioners grows, puzzle solving increases, boosting progress. Higher progress raises confidence, and higher confidence increases recruitment even more. The effect of this loop is to sustain progress at a level in excess of expectations during the growth phase of the paradigm.

The positive feedback loops identified above rapidly raise confidence and membership in the first years of the paradigm's life. In a short span, the practitioners evolve from confusion and doubt to a high degree of faith in the theory. Their confidence allows them to focus their activities on puzzle solving and anomaly resolution. The paradigm has bootstrapped itself into normal science. Between years 70 and 100 the paradigm enjoys unparalled success. confident and unchallenged by rival theories, practitioners make great progress in solving nature's puzzles. Anomalies increase slowly but remain well below the acceptable level. Normal science is at its most productive during this period.

Yet despite the vigor of normal science, underlying conditions are changing. Confidence, after rising rapidly during the emergence phase, starts to level off during the period of normal science. Because doubt and confusion are not particularly pleasant states, practitioners responded quickly to the early successes of the paradigm. Further increases in confidence, however, corresponding to a shift from strong commitment to religious zeal, are slower in coming. More importantly, the pressures causing confidence to rise in the first place diminish, particularly because the relative number of anomalies rises. Anomalies rise despite a gradual shift of practitioners away from puzzle solving into anomaly resolution. The rise is due to the gradual increase in the difficulty of puzzles that comes with the growth of solved puzzles. Higher average difficulty implies more puzzles will be recognized as anomalies before they are incorporated into the theory. In about the 110th year, the number of anomalies rises precipitously, and the effect of anomalies on confidence soon becomes negative for the first time. Over the next decades there is a gradual erosion of confidence as the number of anomalies continues to grow, but because confidence is so great, the anomalies initially make little impression.

The paradigm then enters the crisis phase. As crisis develops, the same self-reinforcing mechanisms that caused confidence and membership to grow so rapidly now work in the opposite direction. As anomalies rise, the fraction of practitioners engaged in puzzle solving declines, reducing the rate of progress and eroding confidence. The process becomes a vicious circle in which lower confidence reduces progress, accelerating the decline in confidence and causing still more people to abandon puzzle solving. Increasing doubt soon lowers the anomaly recognition time. The practitioners increasingly adopt the view that their theory is a limited representation of reality, just as the early practitioners did, and with this recognition comes growing awareness of the holes and rough edges where nature does not go along with the paradigm. Even more anomalies are recognized and confidence is challenged further. In addition, as confidence declines, practitioners lose the dogmatic rigidity they acquired in the period of normal science. As doubts mount, confidence becomes more volatile and responds faster and faster to rising anomalies and inadequate progress.

After one hundred and eighty years, crisis has deepened and accelerated. Confidence is falling at an increasing rate, but only a few practitioners have abandoned sanctioned research and still fewer have left the paradigm altogether. It is interesting that there is a lag of about fifty years (out of a 280 year lifecycle, or more than one sixth the lifetime of the paradigm) between the beginning of the decline in confidence and the beginning of the decline in membership. The model is likely to underestimate the length of this lag since it assumes alternative theories of neutral confidence are always available, while in reality new theories would have to evolve as the crisis developed.

In the next sixty years, crisis becomes revolution. Confidence falls from over three-quarters to about one-quarter, corresponding to a shift from fairly strong belief in the truth of the theory to an equally strong conviction it must be false. Puzzle solving nearly ceases. The fraction of practitioners committed to the paradigm falls from near total dominance to less than half the field. At the end of three centuries the paradigm is essentially dead. Confidence is nearly zero--the paradigm is now viewed as error and superstition. Membership is approaching zero, still lagging behind confidence as a few extremely committed practitioners hang on despite powerful pressure to abandon the paradigm. Such practitioners, like astrologers, would no longer be viewed as scientists by the practitioners of the new paradigm.

In order to test the fundamental hypothesis that it is the gradual exhaustion of the paradigm's root metaphor that causes the revolution, a simulation was performed in which the average difficulty of puzzles was held constant (Figure 11). The first sixty years appear similar to the base case: confidence increases rapidly as there is an initial burst of progress and a low level of anomalies. The level of anomalies increases slightly, but soon stabilizes far below the acceptable level. The number of practitioners rises to one hundred percent of the field, and there is steady growth in solved puzzles. Without the gradual increase of puzzle difficulty anomalies do not increase and confidence rises indefinitely. Normal science continues forever and the paradigm comes to be regarded as absolute truth.

In a second test, the impact of confidence on anomaly recognition was eliminated. Now the positive feedback that suppressed anomalies in the two previous runs is severed; rising familiarity and confidence no longer condition practitioners to 'see' what the paradigm suggests they should see. The result (Figure 12) is striking in that the overall behavior is similar to that of the base run. The major difference is one of timing--the lifecycle is much shorter. Confidence does not increase as high as before, and membership falters before reaching 100%. The test suggests that the degree to which a paradigm conditions a practitioner's perception of reality is not essential in causing revolutions. It does seem to be important, however, in determining the effectiveness of research. Without the suppresive effect of confidence on anomaly recognition, the number of anomalies increases much more rapidly than in the base run, causing confidence to peak and decline just as normal science gets underway. Interestingly, the growth and decline of practitioners still lags confidence by about forty years, peaking just when confidence is falling the fastest.

The lifecycle plays out in about 130 years, compared to 280 in the base case. Thus, it could be argued that the overall rate of progress of science could be enhanced if practitioners did not tend to become rigid in their expectations and perceptions as science progresses, certainly an appealing hypothesis. However, after 46% as much time, the paradigm has produced only 31% as many solved puzzles, a reduction in productivity of one third. The explanation for the reduced productivity lies in the emergence and crisis phases. In both Figure 11 and the base run, emergence and crisis require approximately the same length of time. The major difference between the two simulations is the drastic reduction in the period of normal science when anomaly recognition is divorced from confidence.

When the anomaly recognition time remains low, practitioners are more open to novelty and less bound by traditional ways of seeing, so new theories arise more readily. At the same time, the old theories, because practitioners never achieve the narrow focus normal science depends on, do not probe as deeply into nature as they might. The behavior of the model lends support to Kuhn's statement that "resistance to change has a use":

> By ensuring that the paradigm will not be too easily surrendered, resistance guarantees that scientists will not be lightly distracted and that the anomalies that lead to paradigm change will penetrate existing knowledge to the core. [32]

Sensitivity Tests

To test the sensitivity of these results to the particular numerical assumptions of the model, numerous simulations were performed in which virtually all parameters were varied, typically by factors of 2 or more (the tests are summarized in Table 1). None of the tests changed the fundamental behavior of the lifecycle. Rather, the timing of the lifecycle, particularly the duration of normal science, was primarily affected. Often a change had much

Table 1: Sensitivity of Lifecycle to Major Assumptions

Test conditions	Duration of Lifecycle* (years)	Duration of Normal Science** (years)	Peak Value of Confidence	Total Solved Puzzles
Base case	280	155	.98	5270
Metaphor strength =2*base	445	320	.99	10350
Effect of Anomalies on Confidence =2*base	305	225	.99+	5900
Relative Difficulty of Anomalies = 2 (original = 5)	345	220	.99	6370
Acceptable Anomalies = 4*base	345	220	.99	6210
Goal for Progress = 0%/year (original = 2%/yr)	330	200	.99	5930

* Defined as the year the fraction of practitioners committed to the paradigm drops below 10% of the total.

** Defined as the period during which confidence is greater than .85.

less impact than might be expected. To illustrate, the paradigm-defining metaphor was assumed to be fully twice as strong as in the base case, but the life of the paradigm was prolonged only 165 years, or by 59%. Though normal science lasts twice as long as in the base case, the emergence and crisis phases require the same length of time, reducing the impact of the assumed change on the timing of the lifecycle.

As a further illustration of the insensitivity of the lifecycle to assumptions, a fourfold increase in the acceptable number of anomalies prolongs the lifecycle by 23% and increases the number of solved puzzles by less than 20%. Because practitioners are more tolerant of anomalies, fewer abandon puzzle solving to work on the anomalies, both reducing the rate at which anomalies are solved and increasing the rate of puzzle solving (and hence the increase in puzzle difficulty that leads to anomalies). As a result, anomalies accumulate faster than in the base case, offsetting to some degree the effect of the assumed change. The feedback structure of the system compensates for the change in assumptions, reducing the impact of the change on the timing of the lifecycle. Similar compensating mechanisms account for the generally low sensitivity of the results to changes in other assumptions.

Conclusions

The theory presented here, as tested by the model, supports Kuhn's theory that the lifecycle of scientific theories springs from the ordinary activities of scientists. The lifecycle is a systematic phenomenon with identifiable causes. These causes are feedback processes. It is not necessary to invoke competition between theories or 'great men' hypotheses to account for scientific revolutions.

The model supports the hypothesis that the cause of revolutions is the gradual exhaustion of the root metaphor defining a paradigm. It is not necessary to assume metaphors are finite, only the weaker assumption that they gradually become more difficult to apply as they are used farther from their realm of formulation.

Sensitivity tests reveal the overall behavior of the system to be dominated by its internal structure. Large variations in initial conditions and parameters produce a much smaller range of variation in behavior. The insensitivity is due to compensating feedback mechanisms deeply embedded in the system, suggesting historical circumstance, personalities, diverse content, and sheer luck may play a smaller role in the broad evolution of science than is commonly thought.

At another level, since the theory is largely a representation of Kuhn's vision of science, it shows his theory to be dynamically consistent, that is, it shows the behavior Kuhn sets out to explain can be produced by the forces he postulates. And in a larger sense, the results show how formal models can provide a calculus to test theories of social behavior even when those theories are stated in entirely qualitative terms, at a high level of abstraction, and in a context entirely divorced from explicit dynamic analysis.

NOTES

1. The traditional view, though not homogeneous, is best represented by Popper [2], but see also Campbell [3], Braithwaite [4], and Hempel [5].

2. Paul Feyerabend [6] is the leading advocate of anarchism in science.

3. See, e.g. Lakatos and Musgrave [8] and Kuhn [9].

4. In the course of formalizing Kuhn's theory, certain changes in emphasis and interpretation are necessarily introduced. In particular, the identification of paradigms and metaphors is not an explicit part of Kuhn's theory.

5. Masterman [11] lists 21 distinct senses of the term 'paradigm' in Kuhn [7], and divides these into three main categories: metaphysical, sociological, and artifact paradigms, distinctions similar to those discussed here.

6. Kuhn uses the example of the electricians to illustrate a science before the emergence of its first clear paradigm. The lesson, Kuhn argues, is the same for more mature fields, since during a crisis a science reverts to a state much like the pre-paradigm state.

7. On the mutability of facts, see Kuhn's discussion of the chemical law of fixed proportions (Kuhn [7], pp. 134-135).

8. "Transfer of schema" is Goodman's term (op. cit., pp. 71-80). Gilbert Ryle call the transfer "a calculated category mistake"; Turbayne calls it "sort crossing".

9. A complex philosophical problem is raised here: the nature of 'the literal' or 'the true' from which models are abstracted or the falsity of a metaphor established. The solution to this ancient problem is left to the reader, who is encouraged to adapt the theory of metaphor to any brand of epistemology desired. One solution consistent with the theory of metaphor and paradigms is to assert 'reality' <u>per se</u> cannot be directly perceived, that the sky must always be seen through some sort of smoked glass. Though emerald goggles might be traded for inverting lenses, as in a paradigm change, one cannot gaze with the naked eye on the stuff metaphors are made of. Essentially, the view echoes Lao Tze: "the Tao that can be spoken is not the true Tao."

10. As demonstrated by the case of Galileo, the process of building confidence in Heliocentrism was largely one of personalities, politics, and religion as well as the more usual techniques of data collection, experiment, and logic. See Feyerabend, op. cit.

11. The notion that anomalies arise from dying metaphors sheds an interesting light on a curious aspect of science. When practitioners become disenchanted with a paradigm, its fundamental tenets start to look like tautologies. Poincare noted during the crisis of Newtonian mechanics that 'F=ma' is not a law of nature but merely a definition, since any one of the variables can only be defined in terms of the other two. [28] Similarly, the evolutionary biologist C. H. Waddington, upset with Neo-Darwinist theory, asserted the doctrine of differential reproduction "in fact merely amounts to the statement that the individuals which leave the most offspring are those which leave the most offspring. It is a tautology." [29] The same is true of metaphors that have become trite through overuse. Consider Gertrude Stein's famous quip, once called an epitaph for a dead metaphor: "a rose is a rose is a rose."

12. The crucial experiment or falsificationist view is associated with Sir Karl Popper. [2] See also Lakatos. [31]

13. As an example of paradigm-induced 'blindness', Kuhn (op. cit., pp. 62-65) discusses the Bruner-Postman experiment in which subjects shown anomalous playing cards (e.g. a red six of spades) were unable to identify the card as an anomaly. Even with long exposure times, most people "immediately fitted [the anomalous cards] to one of the conceptual categories prepared by prior experience," i.e., they said 'six of spades' or 'six of hearts'.

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27. Goodman, loc. cit.

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30. Masterman, op. cit., pp. 80, 83.

31. Lakatos, Imre, Proofs and Refutations, Cambridge University Press, London, 1976.

32. Kuhn 1970, p. 65.

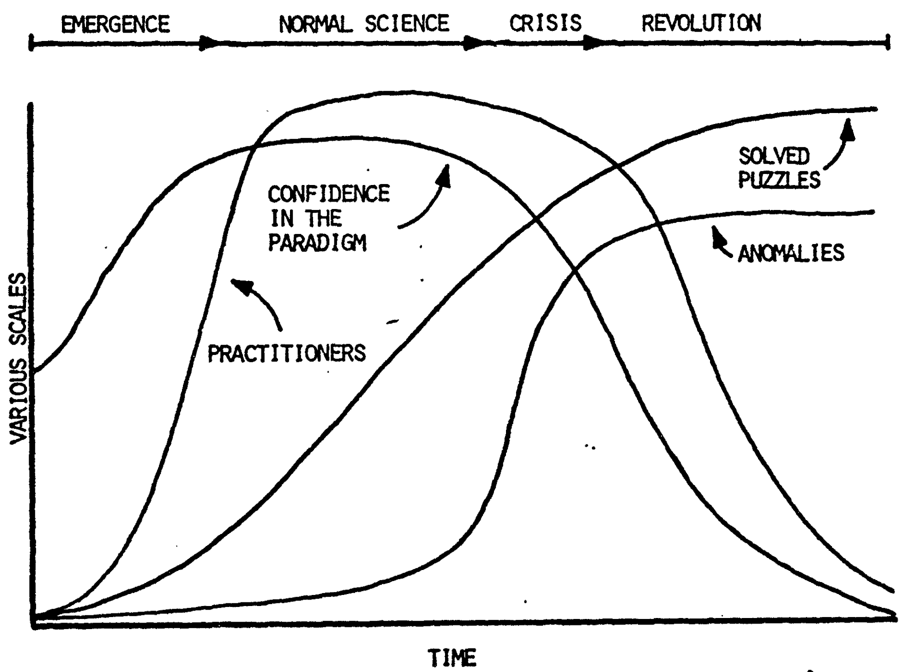

Figure 1. Generic representation of the lifecycle of a paradigm

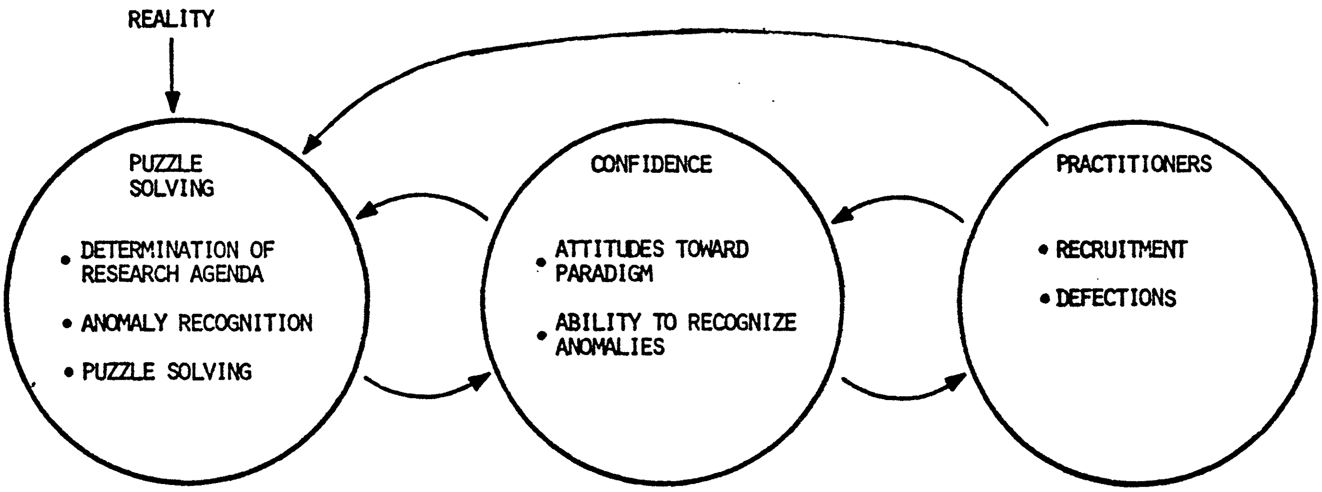

Figure 2. Overview of model structure

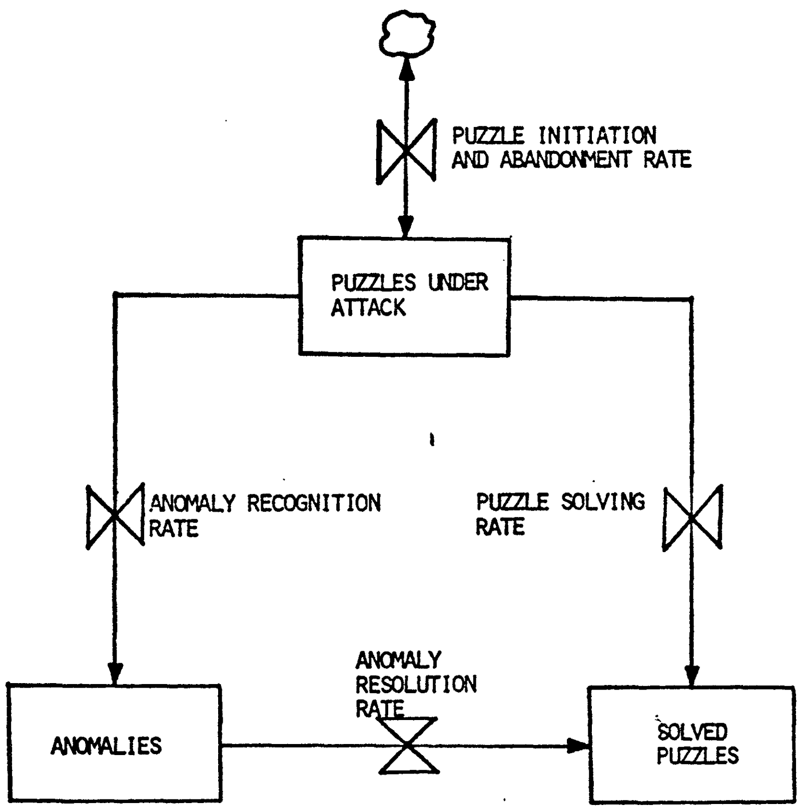

Figure 3. The puzzle solving sector

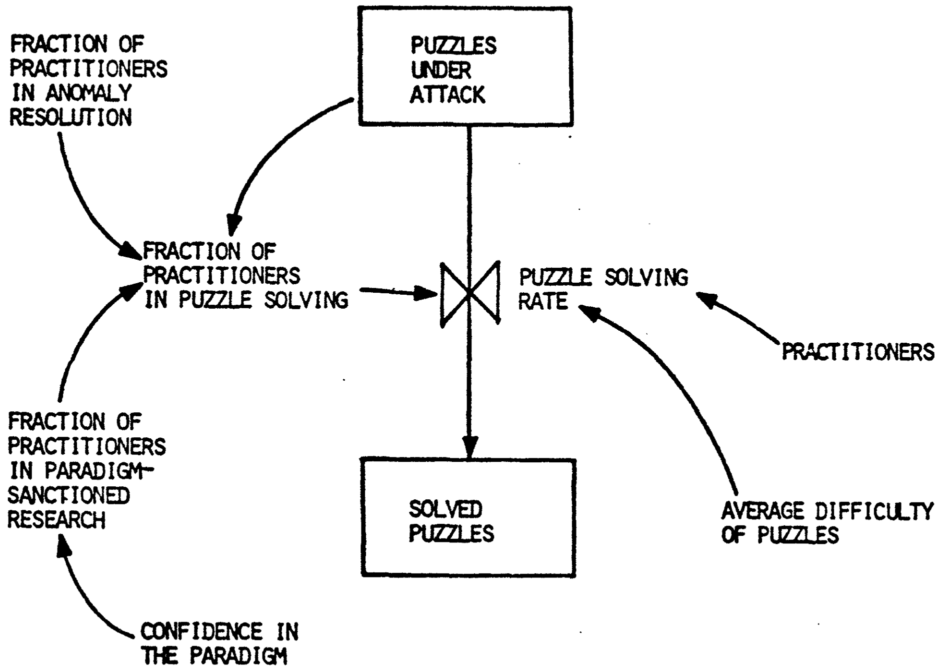

Figure 4. Determinants of the puzzle solving rate

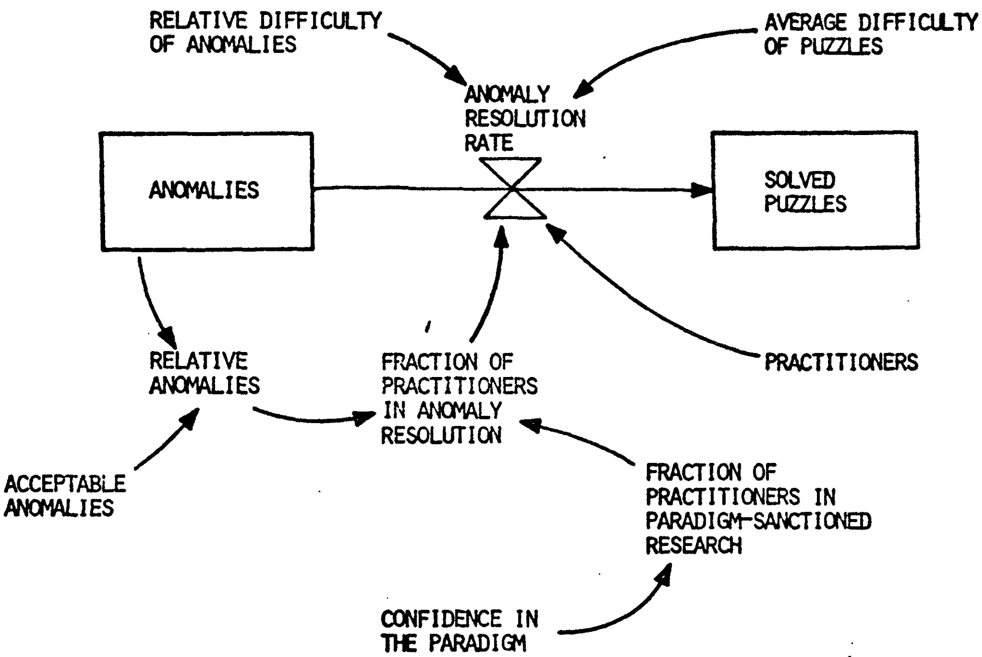

Figure 5. Determinants of the anomaly resolution rate

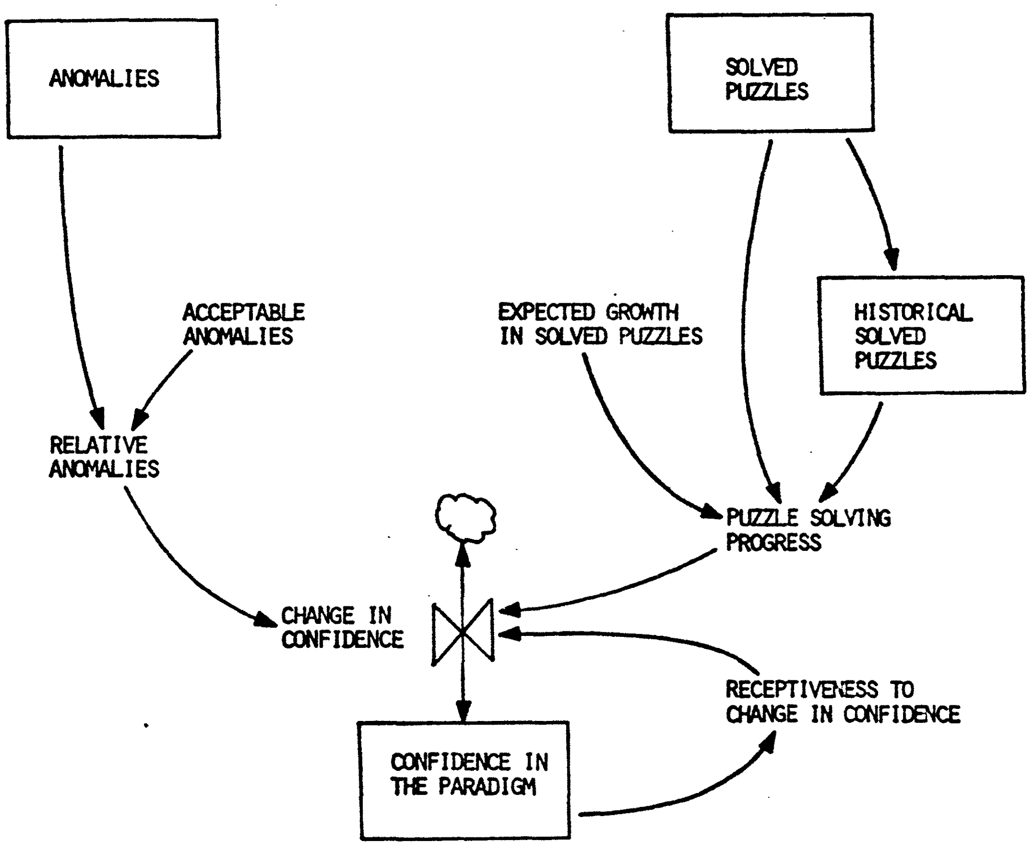

Figure 6. Determinants of confidence in the paradigm

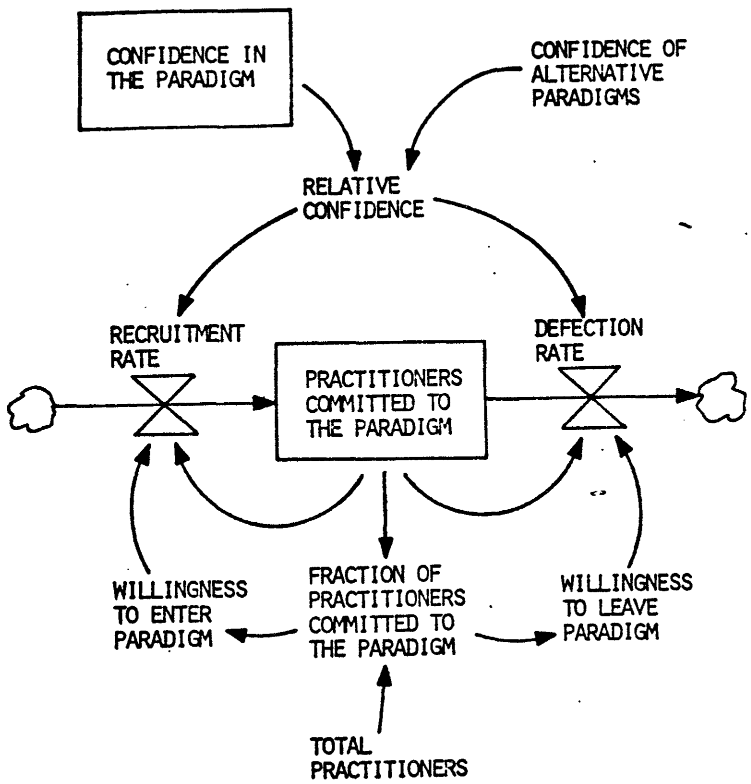

Figure 7. Recruitment and defection of practitioners

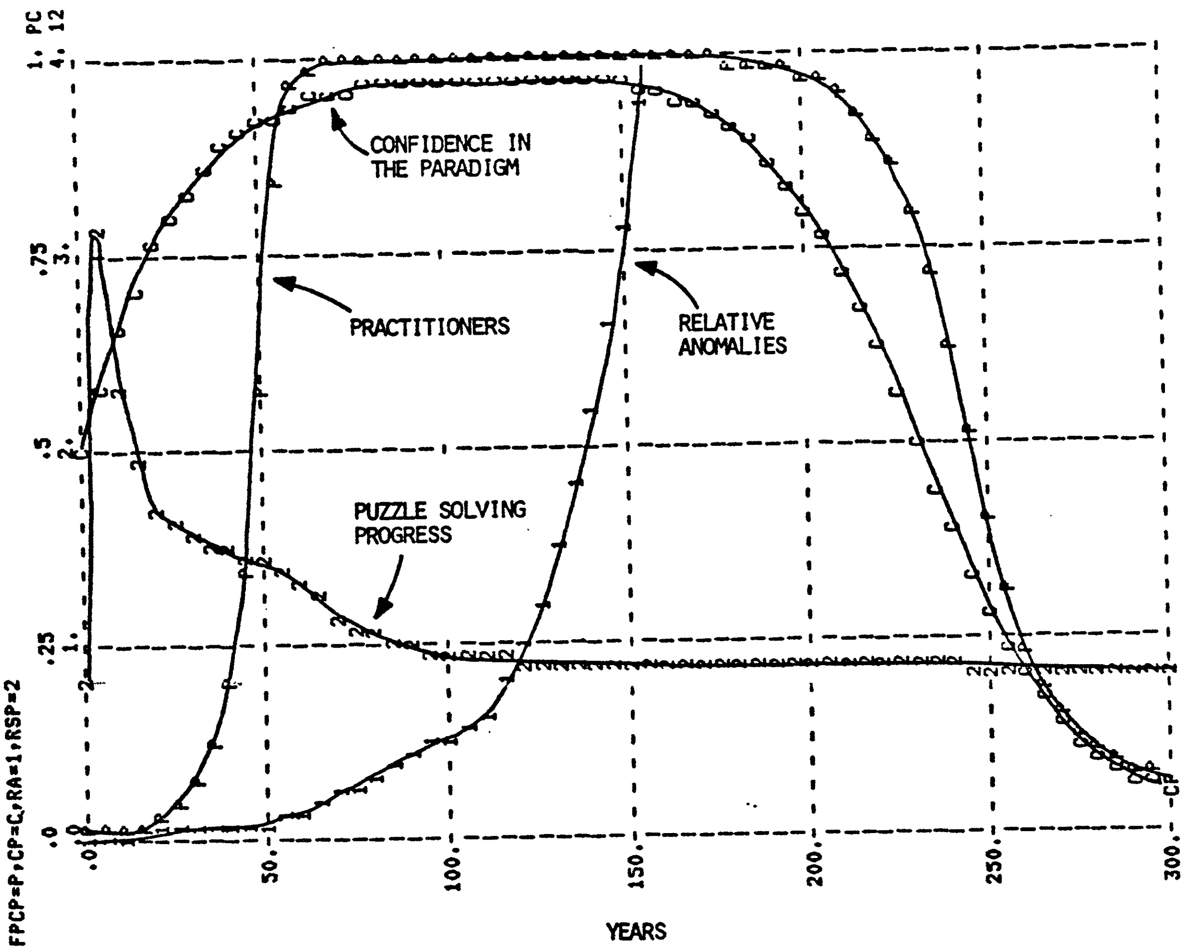

Figure 8a. Base run.

Scales for simulation:

Variable	Units	Range
Practitioners	Fraction of the field	0 - 1
Confidence	Confidence units	0 - 1
Relative anomalies	Dimensionless	0 - 4
Puzzle solving progress	Dimensionless	0 - 4

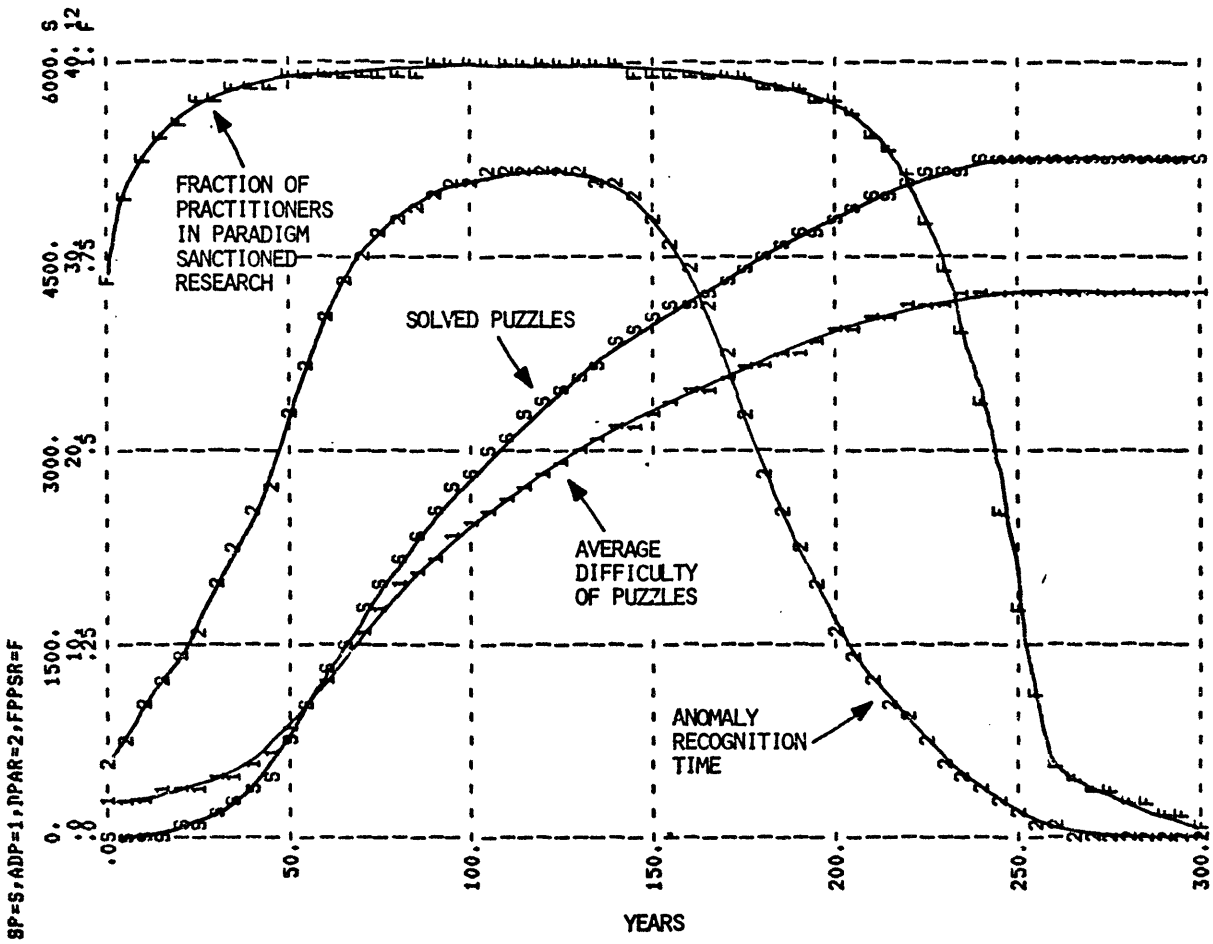

Figure 8b. Base run.

Scales for simulation:

Variable	Units	Range
Solved Puzzles	Puzzles	0 - 6000
Fraction of practitioners in paradigm scanctioned research	Fraction	0 - 1
Average difficulty of puzzles	Person-years/puzzle	0 - 40
Anomaly recognition time	Person-years/puzzle	0 - 40

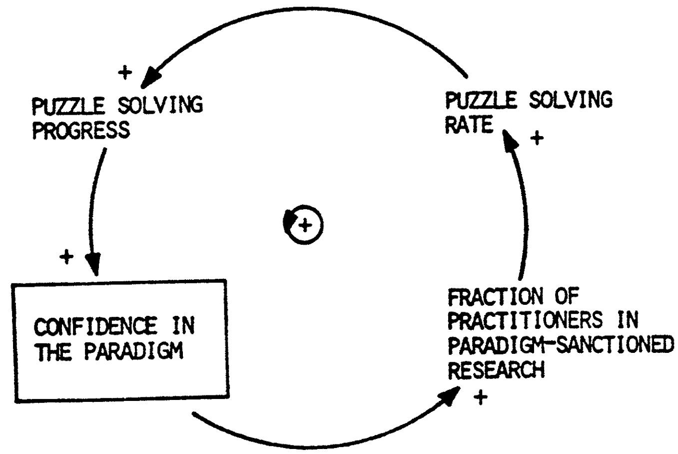

Figure 9. Progress raises confidence, enhancing progress.

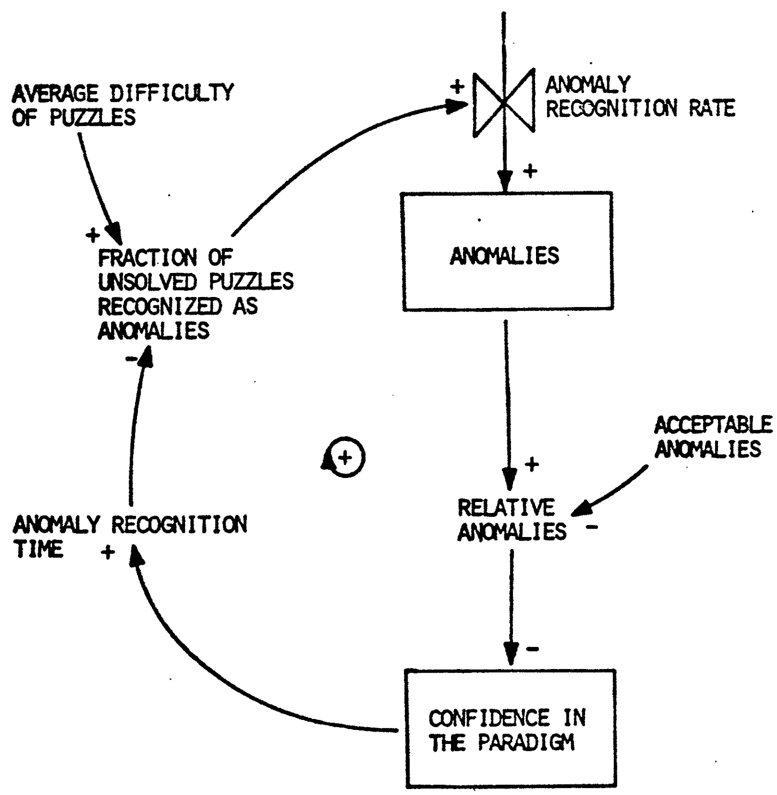

Figure 10. Rising confidence suppresses anomalies, boosting confidence.

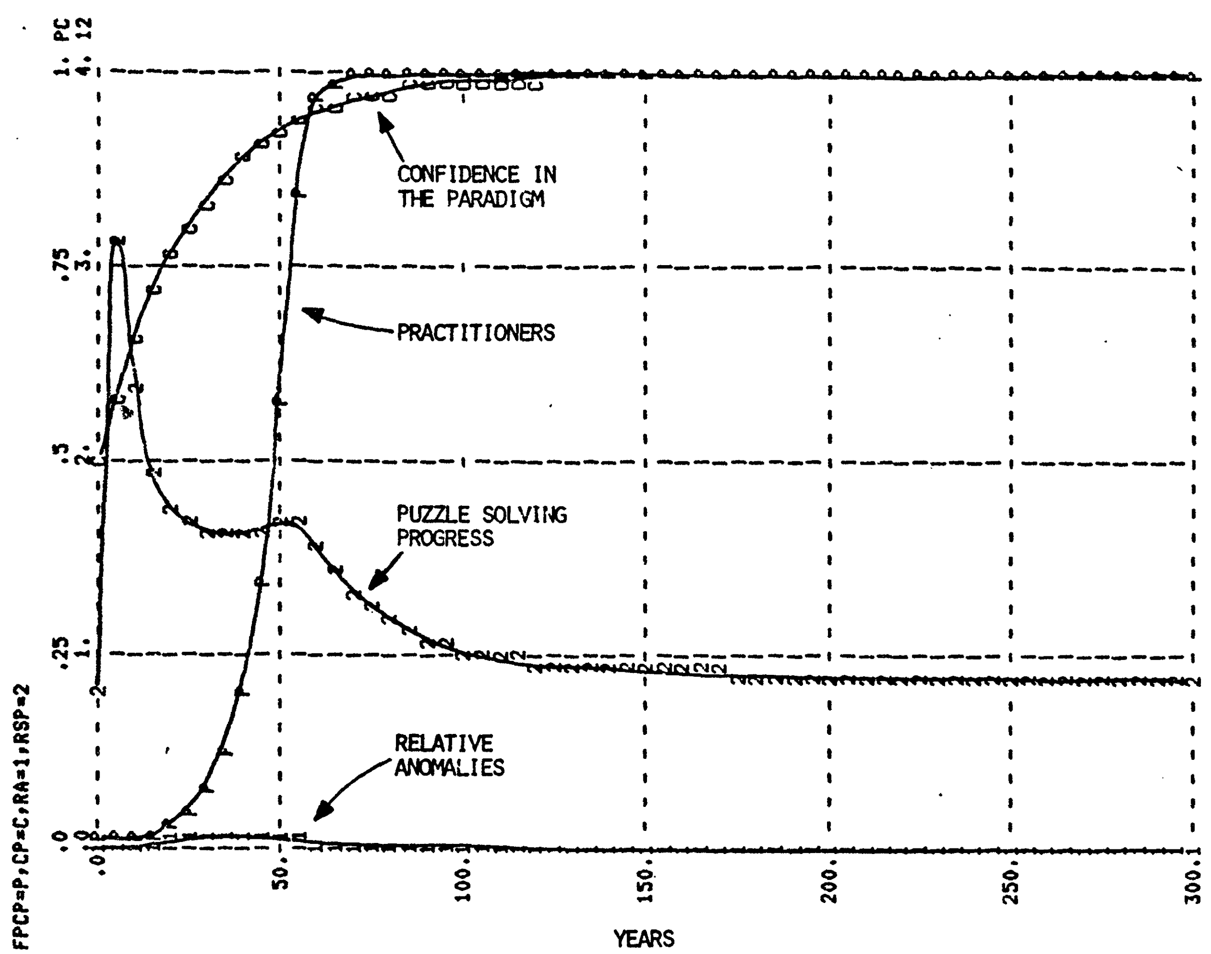

Figure 11a. Constant average difficulty of puzzles

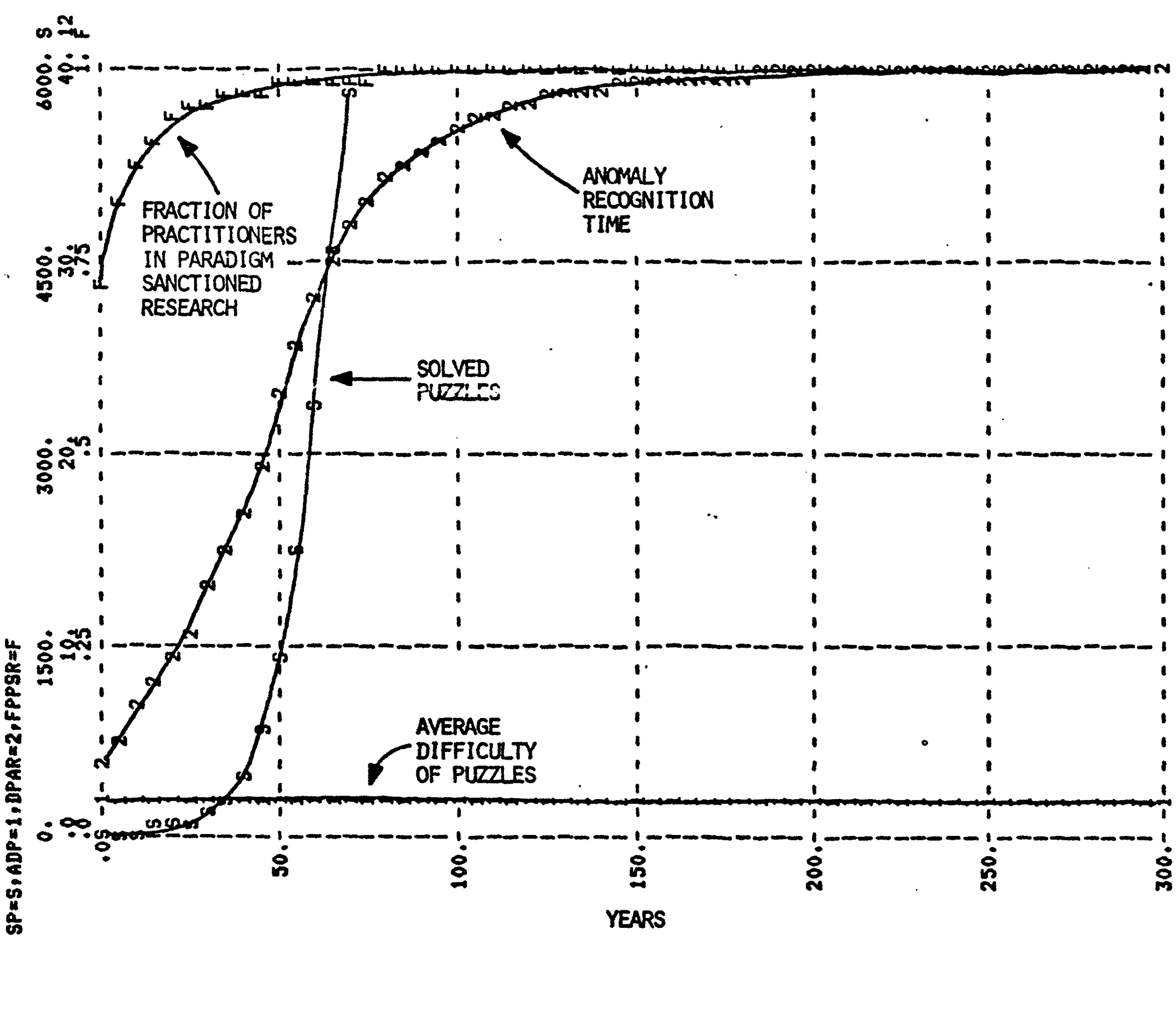

Figure 11b. Constant average difficulty of puzzles

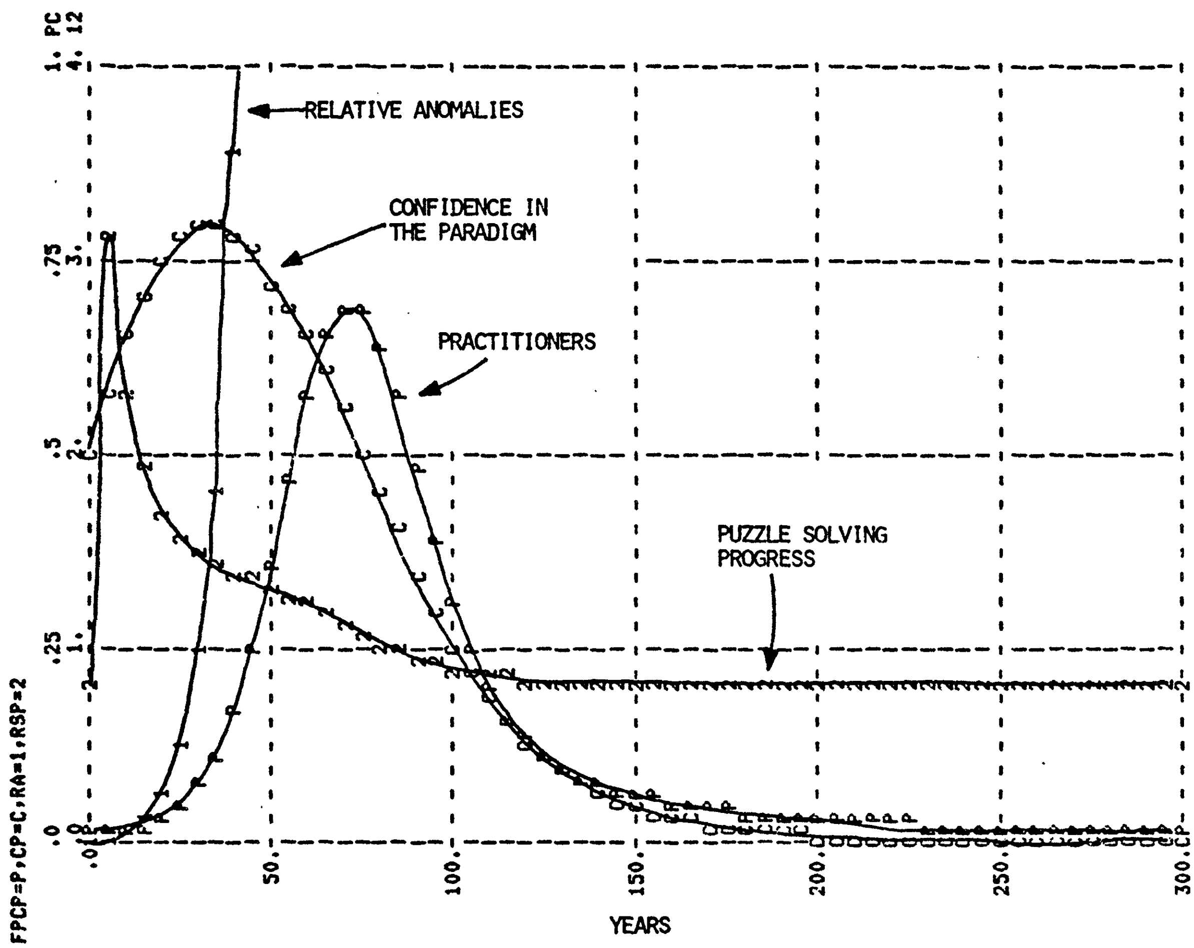

Figure 12a. Constant anomaly recognition time

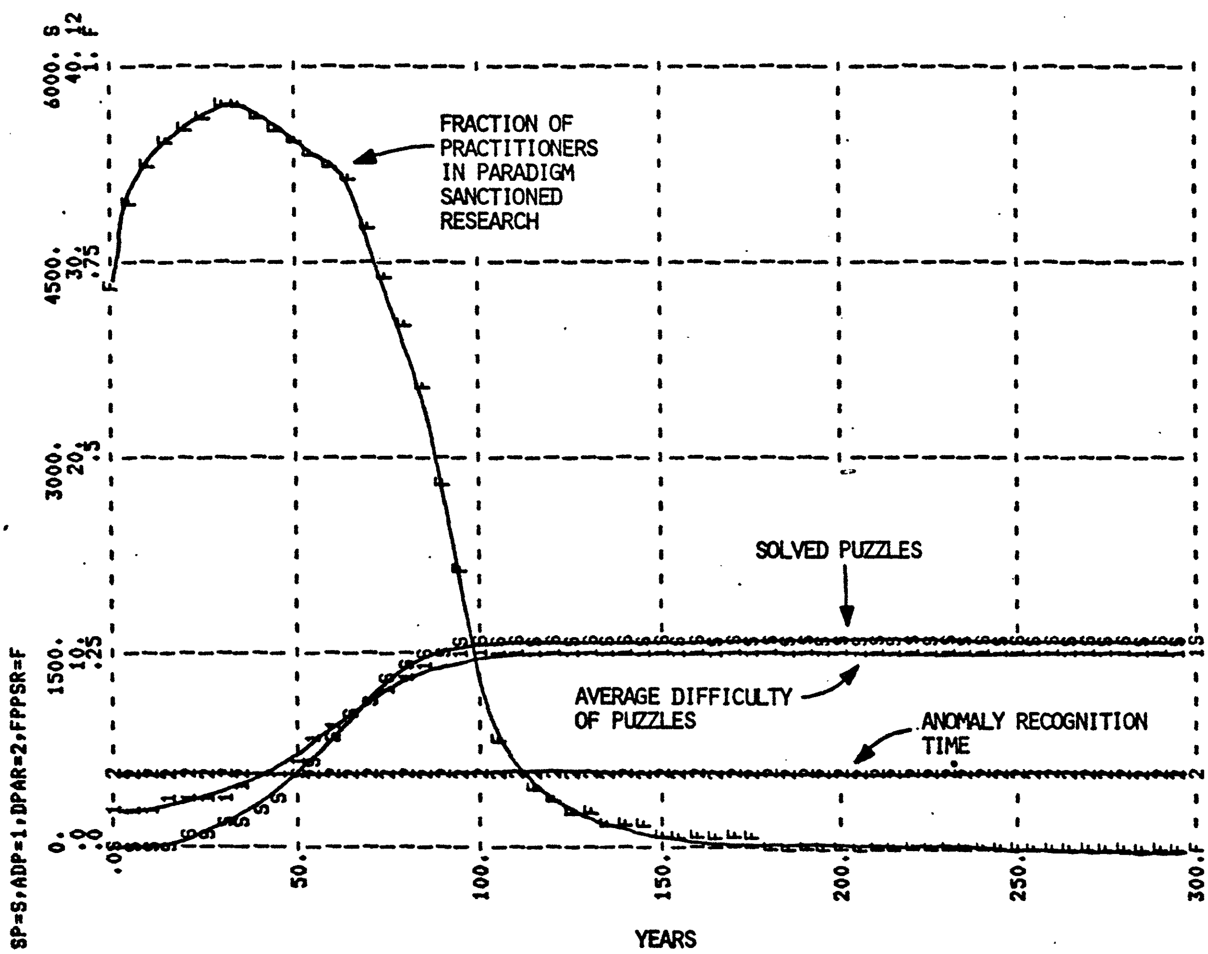

Figure 12b. Constant anomaly recognition time

Appendix: Equation listing and variable definitions

```
DOPT DEFFL,SDOCL,WUOPT=0
* PARADIGM CHANGE
NOTE
NOTE   THE GROWTH OF KNOWLEDGE:
NOTE   TESTING A THEORY OF SCIENTIFIC REVOLUTIONS
NOTE   WITH A FORMAL MODEL
NOTE
NOTE   JOHN D. STERMAN
NOTE
NOTE   SYSTEM DYNAMICS GROUP
NOTE   ALFRED P. SLOAN SCHOOL OF MANAGEMENT
NOTE   MASSACHUSETTS INSITUTE OF TECHNOLOGY
NOTE   CAMBRIDGE MASS 02139
NOTE
NOTE   PUZZLE SOLVING
NOTE
L      SP.K=SP.J+(DT)(PSR.JK+ARESR.JK)
N      SP=ISP
C      ISP=1
R      PSR.KL=PPS.K/ADP.K
A      ADP.K=NDP*EXP(ED*LOGN(1+(SP.K/NSP)))
C      NDP=2
C      ED=1
C      NSP=400
A      PPS.K=P.K*FPPS.K
A      FPPS.K=DFPPS.K*EUPPS.K
A      EUPPS.K=TABHL(TEUPPS,PUA.K/DPUA.K,0,1,.2)
T      TEUPPS=0/.4/.7/.9/.97/1
L      PUA.K=PUA.J+(DT)(PIAR.JK-PSR.JK-ARECR.JK)
N      PUA=DPUA
R      PIAR.KL=PSR.JK+ARECR.JK+CPUA.K
A      CPUA.K=(DPUA.K-PUA.K)/TAPUA
C      TAPUA=1
A      DPUA.K=NPP*P.K*DFPPS.K
C      NPP=1
A      DFPPS.K=FPPSR.K-FPAR.K
A      FPPSR.K=TABLE(TFPPSR,CP.K,0,1,.2)
T      TFPPSR=0/.1/.6/.85/.95/1
A      FPAR.K=FPPSR.K*WPEAR*EAPAR.K
C      WPEAR=.25
A      EAPAR.K=TABHL(TEAPAR,RA.K,0,4,.5)
T      TEAPAR=0/.25/.45/.60/.73/.85/.93/.98/1
A      RA.K=A.K/AA
C      AA=10
L      A.K=A.J+(DT)(ARECR.JK-ARESR.JK)
N      A=IA
C      IA=0
R      ARESR.KL=PAR.K/ADA.K
A      PAR.K=P.K*FPAR.K
A      ADA.K=RDA*ADP.K
C      RDA=5
R      ARECR.KL=EPSR.K*FPRA.K
A      EPSR.K=PPS.K/DPAR.K
A      FPRA.K=TABHL(TFPRA,1.44*LOGN(ADP.K/DPAR.K),-2,2,.5)
T      TFPRA=.01/.02/.04/.2/.5/.8/.96/.98/.99
```

```
00560 NOTE
00570 NOTE  CONFIDENCE
00580 NOTE
00590 A     DPAR.K=NDPAR*ECART.K
00600 C     NDPAR=4
00610 A     ECART.K=TABLE(TECART,CP.K,0,1,.1)
00620 T     TECART=0/.01/.1/.3/.6/1/1.4/1.9/2.6/4.5/10
00630 L     CP.K=CP.J+(DT)(CC.JK)
00640 N     CP=ICP
00650 C     ICP=.5
00660 R     CC.KL=NCC*ICC.K*RCC.K
00670 C     NCC=.002
00680 A     RCC.K=TABLE(TRCC,CP.K,0,1,.1)
00690 T     TRCC=0/.3/.6/.8/.95/1/.95/.8/.6/.3/0
00700 A     ICC.K=CA*EAC.K+CSP*EPC.K
00710 C     CA=1
00720 C     CSP=1
00730 A     EAC.K=TABHL(TEAC,RA.K,0,6,.5)
00740 T     TEAC=5/2.15/0/-1.2/-2.15/-2.9/-3.4/-3.9/-4.4/-4.8/-5.1/-5.3/-5.4
00750 A     EPC.K=TABLE(TEPC,RSP.K,0,5,.5)
00760 T     TEPC=-5/-2.15/0/1.2/2.15/2.9/3.4/3.9/4.2/4.4/4.5
00770 A     RSP.K=SP.K/(HSP.K*(1+EGSP*TEHSP))
00780 L     HSP.K=HSP.J+(DT/TEHSP)(SP.J-HSP.J)
00790 N     HSP=SP
00800 C     TEHSP=10
00810 C     EGSP=.02
00820 NOTE
00830 NOTE  PRACTITIONERS
00840 NOTE
00850 A     FPCP.K=P.K/TP
00860 C     TP=500
00870 L     P.K=P.J+(DT)(RR.JK-DR.JK)
00880 N     P=IP
00890 C     IP=5
00900 R     RR.KL=P.K*NRR*WPEP.K*ECR.K
00910 C     NRR=.04
00920 A     WPEP.K=TABLE(TWPEP,FPCP.K,0,1,.1)
00930 T     TWPEP=1/1/1/1/1/.96/.9/.75/.55/.30/0
00940 A     ECR.K=TABHL(TECR,CP.K/CAP,0,2,.25)
00950 T     TECR=0/.1/.3/.6/1/1.4/2/2.6/3
00960 R     DR.KL=P.K*NDR*WPLP.K*ECD.K
00970 C     NDR=.04
00980 A     WPLP.K=TABLE(TWPLP,FPCP.K,0,1,.1)
00990 T     TWPLP=0/.30/.55/.75/.90/.96/1/1/1/1/1
01000 A     ECD.K=TABHL(TECD,CP.K/CAP,0,2,.25)
01010 T     TECD=3/2.6/2/1.4/1/.6/.3/.1/.01
01020 C     CAP=.5
01030 NOTE
01040 NOTE  CONTROL DATA
01050 NOTE
01060 SPEC DT=.25/LENGTH=300/PLTPER=5/PRTPER=0
01070 PRINT SP,A,FPCP,CP,ADP,DPAR,FPPSR,FPPS,DFPPS,FPAR,FPRA
01080 PLOT FPCP=P,CP=C(0,1)/RA=1,RSP=2(0,4)
01090 PLOT SP=S(0,6E3)/ADP=1,DPAR=2(0,40)/FPPSR=F(0,1)
01100 RUN FIGURE 8
01110 C ED=0
01120 RUN FIGURE 11
01130 C TECART=1/1/1/1/1/1/1/1/1/1/1
01140 RUN FIGURE 12
01150 NOTE
01160 NOTE  TABLE 1 CONSTRUCTED FROM VALUES PRINTED BELOW
01170 NOTE
01180 CP LENGTH=450
01190 CP PRTPER=5
01200 CP PLTPER=0
01210 C NSP=800
01220 RUN METAPHOR STRENGTH = 2*BASE
01230 C CA=2
01240 RUN EFFECT OF ANOMALIES ON CONFIDENCE = 2*BASE
01250 C RDA=2
01260 RUN RELATIVE DIFFICULTY OF ANOMALIES = 2
01270 C AA=40
01280 RUN ACCEPTABLE ANOMALIES = 4*BASE
01290 C EGSP=0
01300 RUN EXPECTED GROWTH IN SOLVED PUZZLES = 0
01310 QUIT
```

LIST OF VARIABLES

SYMBOL	T	WHR-CMP	DEFINITION
A	L	17	ANOMALIES (PUZZLES) <17>
	N	17.1	
AA	C	16.1	ACCEPTABLE ANOMALIES (PUZZLES) <16>
ADA	A	20	AVERAGE DIFFICULTY OF ANOMALIES (PERSON-YEARS/ PUZZLE) <20>
ADP	A	4	AVERAGE DIFFICULTY OF PUZZLES (DIMENSIONLESS) <4>
ARECR	R	21	ANOMALY RECOGNITION RATE (PUZZLES/YEAR) <21>
ARESR	R	18	ANOMALY RESOLUTION RATE (PUZZLES/YEAR) <18>
CA	C	29.1	COEFFICIENT FOR ANOMALIES (DIMENSIONLESS) <29>
CAP	C	41.2	CONFIDENCE OF ALTERNATIVE PARADIGMS (CONFIDENCE UNITS) <41>
CC	R	27	CHANGE IN CONFIDENCE (CONFIDENCE UNITS/YEAR) <27>
CF	L	26	CONFIDENCE IN THE PARADIGM (CONFIDENCE UNITS) <26>
	N	26.1	
CPUA	A	10	CORRECTION FOR PUZZLES UNDER ATTACK (PUZZLES/ YEAR) <10>
CSP	C	29.2	COEFFICIENT FOR SOLVED PUZZLES (DIMENSIONLESS) <29>
DFPPS	A	12	DESIRED FRACTION OF PRACTITIONERS IN PUZZLE SOLVING (FRACTION) <12>
DPAR	A	24	DIFFICULTY OF PUZZLES FOR ANOMALY RECOGNITION (PERSON-YEARS/PUZZLE) <24>
DPUA	A	11	DESIRED PUZZLES UNDER ATTACK (PUZZLES) <11>
DR	R	39	DEFECTION RATE (PERSONS/YEAR) <39>
DT	S	42	SOLUTION INTERVAL (YEARS) <42>
EAC	A	30	EFFECT OF ANOMALIES ON CONFIDENCE (DIMENSIONLESS) <30>
EAPAR	A	15	EFFECT OF ANOMALIES ON PRACTITIONERS IN ANOMALY RESOLUTION (DIMENSIONLESS) <15>
ECART	A	25	EFFECT OF CONFIDENCE ON ANOMALY RECOGNITION TIME (DIMENSIONLESS) <25>
ECD	A	41	EFFECT OF CONFIDENCE ON DEFECTIONS (DIMENSIONLESS) <41>
ECR	A	38	EFFECT OF CONFIDENCE ON RECRUITMENT (DIMENSIONLESS) <38>
ED	C	4.2	ELASTICITY OF PUZZLE DIFFICULTY WITH RESPECT TO SOLVED PUZZLES (DIMENSIONLESS) <4>
EGSP	C	33.3	EXPECTED GROWTH IN SOLVED PUZZLES (FRACTION/ YEAR) <33>
EPC	A	31	EFFECT OF PROGRESS ON CONFIDENCE (DIMENSIONLESS) <31>
EPSR	A	22	EXPECTED POUZZLE SOLVING RATE (PUZZLES/YEAR) <22>
EUPPS	A	7	EFFECT OF UNSOLVED PUZZLES ON PUZZLE SOLVING (DIMENSIONLESS) <7>
EXP			EXPONENTIAL FUNCTION
FPAR	A	14	FRACTION OF PRACTITIONERS IN ANOMALY RESOLUTION (FRACTION) <14>
FPCP	A	34	FRACTION OF PRACTITIONERS COMMITTED TO THE PARADIGM (FRACTION) <34>
FPPS	A	6	FRACTION OF PRACTITIONERS IN PUZZLE SOLVING (FRACTION) <6>
FPPSR	A	13	FRACTION OF PRACTITIONERS IN PARADIGM SANCTIONED RESEARCH (FRACTION) <13>
FPRA	A	23	FRACTION OF PUZZLES RECOGNIZED AS ANOMALIES (FRACTION) <23>
HSP	L	33	HISTORICAL SOLVED PUZZLES (PUZZLES) <33>
	N	33.1	
IA	C	17.2	INITIAL ANOMALIES (PUZZLES) <17>
ICC	A	29	INDICATED CHANGE IN CONFIDENCE (DIMENSIONLESS) <29>
ICP	C	26.2	INITIAL CONFIDENCE IN THE PARADIGM (CONFIDENCE UNITS) <26>
IP	C	35.2	INITIAL PRACTITIONERS (PERSONS) <35>
ISP	C	2.2	INITIAL SOLVED PUZZLES (PUZZLES) <2>
LENGTH	S	42	SIMULATION LENGTH (YEARS) <42>
LOGN			NATURAL LOGARITHM

NCC	C	27.1	NORMAL CHANGE IN CONFIDENCE (CONFIDENCE UNITS/ YEAR) <27>
NDP	C	4.1	NORMAL DIFFICULTY OF PUZZLES (PERSON-YEARS/ PUZZLE) <4>
NDPAR	C	24.1	NORMAL DIFFICULTY OF PUZZLES FOR ANOMALY RECOGNITION (PERSON-YEARS/PUZZLE) <24>
NDR	C	39.1	NORMAL DEFECTION RATE (FRACTION/YEAR) <39>
NPP	C	11.1	NORMAL PUZZLES PER PRACTITIONER (PUZZLES/PERSON) <11>
NRR	C	36.1	NORMAL RECRUITMENT RATE (FRACTION/YEAR) <36>
NSP	C	4.3	NORMAL SOLVED PUZZLES (PUZZLES) <4>
P	L	35	PRACTITIONERS (PERSONS) <35>
	N	35.1	
PAR	A	19	PRACTITIONERS IN ANOMALY RESOLUTION (PERSONS) <19>
PIAR	R	9	PUZZLE INITIATION AND ABANDONMENT RATE (PUZZLES/ YEAR) <9>
PLTPER	S	42	PLOT PERIOD (YEARS) <42>
PPS	A	5	PRACTITIONERS IN PUZZLE SOLVING (PERSONS) <5>
PRTPER	S	42	PRINT PERIOD (YEARS) <42>
PSR	R	3	PUZZLE SOLVING RATE (PUZZLES/YEAR) <3>
PUA	L	8	PUZZLES UNDER ATTACK (PUZZLES) <8>
	N	8.1	
RA	A	16	RELATIVE ANOMALIES (DIMENSIONLESS) <16>
RCC	A	28	RECEPTIVENESS TO CHANGE IN CONFIDENCE (DIMENSIONLESS) <28>
RDA	C	20.1	RELATIVE DIFFICULTY OF ANOMALIES (DIMENSIONLESS) <20>
RR	R	36	RECRUITMENT RATE (PERSONS/YEAR) <36>
RSP	A	32	RELATIVE SOLVED PUZZLES (DIMENSIONLESS) <32>
SP	L	2	SOLVED PUZZLES (PUZZLES) <2>
	N	2.1	
TABHL			FUNCTION TO REPRESENT NONLINEAR RELATIONSHIP
TABLE			FUNCTION TO REPRESENT NONLINEAR RELATIONSHIP
TAPUA	C	10.1	TIME TO ADJUST PUZZLES UNDER ATTACK (YEARS) <10>
TEAC	T	30.1	TABLE FOR EFFECT OF ANOMALIES ON CONFIDENCE <30>
TEAPAR	T	15.1	TABLE FOR EFFECT OF ANOMALIES ON PRACTITIONERS IN ANOMALY RESOLUTION <15>
TECART	T	25.1	TABLE FOR EFFECT OF CONFIDENCE ON ANOMALY RECOGNITION TIME <25>
TECD	T	41.1	TABLE FOR EFFECT OF CONFIDENCE ON DEFECTIONS <41>
TECR	T	38.1	TABLE FOR EFFECT OF CONFIDENCE ON RECRUITMENT <38>
TEHSP	C	33.2	TIME TO ESTABLISH HISTORICAL SOLVED PUZZLES (YEARS) <33>
TEPC	T	31.1	TABLE FOR EFFECT OF PROGRESS ON CONFIDENCE <31>
TEUPPS	T	7.1	TABLE FOR EFFECT OF UNSOLVED PUZZLES ON PUZZLE SOLVING <7>
TFPPSR	T	13.1	TABLE FOR FRACTION OF PRACTITIONERS IN PARADIGM SANCTIONED RESEARCH <13>
TFPRA	T	23.1	TABLE FOR FRACTION OF PUZZLES RECOGNIZED AS ANOMALIES <23>
TP	C	34.1	TOTAL PRACTITIONERS (PERSONS) <34>
TRCC	T	28.1	TABLE FOR RECEPTIVENESS TO CHANGE IN CONFIDENCE <28>
TWPEP	T	37.1	TABLE FOR WILLINGNESS OF PRACTITIONERS TO ENTER PARADIGM <37>
TWPLP	T	40.1	TABLE FOR WILLINGNESS OF PRACTITIONERS TO LEAVE PARADIGM <40>
WPEAR	C	14.1	WILLINGNESS OF PRACTITIONERS TO ENTER ANOMALY RESOLUTION (FRACTION) <14>
WPEP	A	37	WILLINGNESS OF PRACTITIONERS TO ENTER PARADIGM (DIMENSIONLESS) <37>
WPLP	A	40	WILLINGNESS OF PRACTITIONERS TO LEAVE PARADIGM (DIMENSIONLESS) <40>