The Structure of Scientific Revolutions

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I Introduction

A scientific community cannot practice its trade without some set of received beliefs. These beliefs form the foundation of the "educational initiation that prepares and licenses the student for professional practice". The nature of the "rigorous and rigid" preparation helps ensure that the received beliefs are firmly fixed in the student's mind. Scientists take great pains to defend the assumption that scientists know what the world is like...To this end, "normal science" will often suppress novelties which undermine its foundations. Research is therefore not about discovering the unknown, but rather "a strenuous and devoted attempt to force nature into the conceptual boxes supplied by professional education".

A shift in professional commitments to shared assumptions takes place when an anomaly undermines the basic tenets of the current scientific practice These shifts are what Kuhn describes as scientific revolutions - "the tradition-shattering complements to the tradition-bound activity of normal science" New assumptions – "paradigms" - require the reconstruction of prior assumptions and the re-evaluation of prior facts. This is difficult and time consuming. It is also strongly resisted by the established community.

II The Route to Normal Science

So how are paradigms created and what do they contribute to scientific inquiry?

Normal science "means research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice". These achievements must be sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity and sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners (and their students) to resolve. These achievements can be called paradigms. Students study these paradigms in order to become members of the particular scientific community in which they will later practice.

Because the student largely learns from and is mentored by researchers "who learned the bases of their field from the same concrete models" there is seldom disagreement over fundamentals. Men whose research is based on shared paradigms are committed to the same rules and standards for scientific practice. A shared commitment to a paradigm ensures that its practitioners engage in the paradigmatic observations that its own paradigm can do most to explain. Paradigms help scientific communities to bound their discipline in that they help the scientist to create avenues of inquiry, formulate questions, select methods with which to examine questions, define areas of relevance. and establish or create meaning. A paradigm is essential to scientific inquiry - "no natural history can be interpreted in the absence of at least some implicit body of intertwined theoretical and methodological belief that permits selection, evaluation, and criticism".

How are paradigms created, and how do scientific revolutions take place? Inquiry begins with a random collection of "mere facts" (although, often, a body of beliefs is already implicit in the collection). During these early stages of inquiry, different researchers confronting the same phenomena describe and interpret them in different ways. In time, these descriptions and interpretations entirely disappear. A pre-paradigmatic school appears. Such a school often emphasises a special part of the collection of facts. Often, these schools vie for pre-eminence.

From the competition of these pre-paradigmatic schools, one paradigm emerges - "To be accepted as a paradigm, a theory must seem better than its competitors, but it need not, and in fact never does, explain all the facts with which it can be confronted", thus making research possible. As a paradigm grows in strength and in the number of advocates, the other pre-paradigmatic schools or the previous paradigm fade.

A paradigm transforms a group into a profession or, at least, a discipline. And from this follow the formation of specialised journals, foundation of professional bodies and a claim to a special place in academe. There is a promulgation of scholarly articles intended for and "addressed only to professional colleagues, [those] whose knowledge of a shared paradigm can be assumed and who prove to be the only ones able to read the papers addressed to them".

III - The Nature of Normal Science.

If a paradigm consists of basic and incontrovertible assumptions about the nature of the discipline, what questions are left to ask?

When they first appear, paradigms are limited in scope and in precision. But more successful does not mean completely successful with a single problem or notably successful with any large number. Initially, a paradigm offers the promise of success. Normal science consists in the actualisation of that promise. This is achieved by extending the knowledge of those facts that the paradigm displays as particularly revealing, increasing the extent of the match between those facts and the paradigm's predictions, and further articulation of the paradigm itself.

In other words, there is a good deal of mopping-up to be done. Mop-up operations are what engage most scientists throughout their careers. Mopping-up is what normal science is all about! This paradigm-based research is "an attempt to force nature into the pre-formed and relatively inflexible box that the paradigm supplies". No effort is made to call forth new sorts of phenomena, no effort to discover anomalies. When anomalies pop up, they are usually discarded or ignored. Anomalies are usually not even noticed and no effort is made to invent a new theory (and there's no tolerance for those who try). Those restrictions, born from confidence in a paradigm, turn out to be essential to the development of science. By focusing attention on a small range of relatively esoteric problems, the paradigm forces scientists to investigate some part of nature in a detail and depth that would otherwise be unimaginable" and, when the paradigm ceases to function properly, scientists begin to behave differently and the nature of their research problems changes.

IV - Normal Science as Puzzle-solving.

Doing research is essentially like solving a puzzle. Puzzles have rules. Puzzles generally have predetermined solutions.

A striking feature of doing research is that the aim is to discover what is known in advance. This in spite of the fact that the range of anticipated results is small compared to the possible results. When the outcome of a research project does not fall into this anticipated result range, it is generally considered a failure.

So why do research? Results add to the scope and precision with which a paradigm can be applied. The way to obtain the results usually remains very much in doubt - this is the challenge of the puzzle. Solving the puzzle can be fun, and expert puzzle-solvers make a very nice living. To classify as a puzzle (as a genuine research question), a problem must be characterised by more than the assured solution, but at the same time solutions should be consistent with paradigmatic assumptions.

Despite the fact that novelty is not sought and that accepted belief is generally not challenged, the scientific enterprise can and does bring about unexpected results.

V - The Priority of Paradigms.

The paradigms of a mature scientific community can be determined with relative ease. The "rules" used by scientists who share a paradigm are not so easily determined. Some reasons for this are that scientists can disagree on the interpretation of a paradigm. The existence of a paradigm need not imply that any full set of rules exist. Also, scientists are often guided by tacit knowledge - knowledge acquired through practice and that cannot be articulated explicitly. Further, the attributes shared by a paradigm are not always readily apparent.

Paradigms can determine normal science without the intervention of discoverable rules or shared assumptions. In part, this is because it is very difficult to discover the rules that guide particular normal-science traditions. Scientists never learn concepts, laws, and theories in the abstract and by themselves. They generally learn these with and through their applications. New theory is taught in tandem with its application to a concrete range of phenomena.

Sub-specialties are differently educated and focus on different applications for their research findings. A paradigm can determine several traditions of normal science that overlap without being coextensive. Consequently, changes in a paradigm affect different sub-specialties differently. "A revolution produced within one of these traditions will not necessarily extend to the others as well".

When scientists disagree about whether the fundamental problems of their field have been solved, the search for rules gains a function that it does not ordinarily possess .

VI - Anomaly and the Emergence of Scientific Discoveries.

If normal science is so rigid and if scientific communities are so close-knit, how can a paradigm change take place? Paradigm changes can result from discovery brought about by encounters with anomaly.

Normal science does not aim at novelties of fact or theory and, when successful, finds none. Nonetheless, new and unsuspected phenomena are repeatedly uncovered by scientific research, and radical new theories have again and again been invented by scientists . Fundamental novelties of fact and theory bring about paradigm change. So how does paradigm change come about? There are two ways: through discovery - novelty of fact - or by invention – novelty of theory. Discovery begins with the awareness of anomaly - the recognition that nature has violated the paradigm-induced expectations that govern normal science. The area of the anomaly is then explored. The paradigm change is complete when the paradigm has been adjusted so that the anomalous become the expected. The result is that the scientist is able "to see nature in a different way".. How paradigms change as a result of invention is discussed in greater detail in the following chapter.

Although normal science is a pursuit not directed to novelties and tending at first to suppress them, it is nonetheless very effective in causing them to arise. Why? An initial paradigm accounts quite successfully for most of the observations and experiments readily accessible to that science's practitioners. Research results in the construction of elaborate equipment, development of an esoteric and shared vocabulary, refinement of concepts that increasingly lessens their resemblance to their usual common-sense prototypes. This professionalisation leads to immense restriction of the scientist's vision, rigid science, resistance to paradigm change, and a detail of information and precision of the observation-theory match that can be achieved in no other way. New and refined methods and instruments result in greater precision and understanding of the paradigm. Only when researchers know with precision what to expect from an experiment can they recognise that something has gone wrong.

Consequently, anomaly appears only against the background provided by the paradigm . The more precise and far-reaching the paradigm, the more sensitive it is to detecting an anomaly and inducing change. By resisting change, a paradigm guarantees that anomalies that lead to paradigm change will penetrate existing knowledge to the core.

VII - Crisis and the Emergence of Scientific Theories.

As is the case with discovery, a change in an existing theory that results in the invention of a new theory is also brought about by the awareness of anomaly. The emergence of a new theory is generated by the persistent failure of the puzzles of normal science to be solved as they should. Failure of existing rules is the prelude to a search for new ones . These failures can be brought about by observed discrepancies between theory and fact or changes in social/cultural climates Such failures are generally long recognised, which is why crises are seldom surprising. Neither problems nor puzzles yield often to the first attack . Recall that paradigm and theory resist change and are extremely resilient. Philosophers of science have repeatedly demonstrated that more than one theoretical construction can always be placed upon a given collection of data . In early stages of a paradigm, such theoretical alternatives are easily invented. Once a paradigm is entrenched (and the tools of the paradigm prove useful to solve the problems the paradigm defines), theoretical alternatives are strongly resisted. As in manufacture so in science--retooling is an extravagance to be reserved for the occasion that demands it . Crises provide the opportunity to retool.

VIII - The Response to Crisis.

The awareness and acknowledgement that a crisis exists loosens theoretical stereotypes and provides the incremental data necessary for a fundamental paradigm shift. Normal science does and must continually strive to bring theory and fact into closer agreement. The recognition and acknowledgement of anomalies result in crises that are a necessary precondition for the emergence of novel theories and for paradigm change. Crisis is the essential tension implicit in scientific research. There is no such thing as research without counterinstances. These counterinstances create tension and crisis. Crisis is always implicit in research because every problem that normal science sees as a puzzle can be seen, from another viewpoint, as a counterinstance and thus as a source of crisis .

In responding to these crises, scientists generally do not renounce the paradigm that has led them into crisis. Rather, they usually devise numerous articulations and ad hoc modifications of their theory in order to eliminate any apparent conflict. Some, unable to tolerate the crisis, leave the profession. As a rule, persistent and recognised anomaly does not induce crisis . Failure to achieve the expected solution to a puzzle discredits only the scientist and not the theory To evoke a crisis, an anomaly must usually be more than just an anomaly. Scientists who paused and examined every anomaly would not get much accomplished. An anomaly must come to be seen as more than just another puzzle of normal science.

All crises begin with the blurring of a paradigm and the consequent loosening of the rules for normal research. As this process develops, the anomaly comes to be more generally recognised as such, more attention is devoted to it by more of the field's eminent authorities. The field begins to look quite different: scientists express explicit discontent, competing articulations of the paradigm proliferate and scholars view a resolution as the subject matter of their discipline. To this end, they first isolate the anomaly more precisely and give it structure. They push the rules of normal science harder than ever to see, in the area of difficulty, just where and how far they can be made to work.

All crises close in one of three ways. (i) Normal science proves able to handle the crisis-provoking problem and all returns to "normal." (ii) The problem resists and is labelled, but it is perceived as resulting from the field's failure to possess the necessary tools with which to solve it, and so scientists set it aside for a future generation with more developed tools. (iii) A new candidate for paradigm emerges, and a battle over its acceptance ensues. Once it has achieved the status of paradigm, a paradigm is declared invalid only if an alternate candidate is available to take its place . Because there is no such thing as research in the absence of a paradigm, to reject one paradigm without simultaneously substituting another is to reject science itself. To declare a paradigm invalid will require more than the falsification of the paradigm by direct comparison with nature. The judgement leading to this decision involves the comparison of the existing paradigm with nature and with the alternate candidate. Transition from a paradigm in crisis to a new one from which a new tradition of normal science can emerge is not a cumulative process. It is a reconstruction of the field from new fundamentals. This reconstruction changes some of the field's foundational theoretical generalisations. It changes methods and applications. It alters the rules.

How do new paradigms finally emerge? Some emerge all at once, sometimes in the middle of the night, in the mind of a man deeply immersed in crisis. Those who achieve fundamental inventions of a new paradigm have generally been either very young or very new to the field whose paradigm they changed. Much of this process is inscrutable and may be permanently so.

IX - The Nature and Necessity of Scientific Revolutions.

Why should a paradigm change be called a revolution? What are the functions of scientific revolutions in the development of science?

A scientific revolution is a non-cumulative developmental episode in which an older paradigm is replaced in whole or in part by an incompatible new one . A scientific revolution that results in paradigm change is analogous to a political revolution. Political revolutions begin with a growing sense by members of the community that existing institutions have ceased adequately to meet the problems posed by an environment that they have in part created. The dissatisfaction with existing institutions is generally restricted to a segment of the political community. Political revolutions aim to change political institutions in ways that those institutions themselves prohibit. As crisis deepens, individuals commit themselves to some concrete proposal for the reconstruction of society in a new institutional framework. Competing camps and parties form. One camp seeks to defend the old institutional constellation. One (or more) camps seek to institute a new political order. As polarisation occurs, political recourse fails. Parties to a revolutionary conflict finally resort to the techniques of mass persuasion.

Like the choice between competing political institutions, that between competing paradigms proves to be a choice between fundamentally incompatible modes of community life. Paradigmatic differences cannot be reconciled. When paradigms enter into a debate about fundamental questions and paradigm choice, each group uses its own paradigm to argue in that paradigm's defence The result is a circularity and inability to share a universe of discourse. A successful new paradigm permits predictions that are different from those derived from its predecessor . That difference could not occur if the two were logically compatible. In the process of being assimilated, the second must displace the first.

Consequently, the assimilation of either a new sort of phenomenon or a new scientific theory must demand the rejection of an older paradigm . If this were not so, scientific development would be genuinely cumulative. Normal research is cumulative, but not scientific revolution. New paradigms arise with destructive changes in beliefs about nature.

Consequently, "the normal-scientific tradition that emerges from a scientific revolution is not only incompatible but often actually incommensurable with that which has gone before". In the circular argument that results from this conversation, each paradigm will satisfy more or less the criteria that it dictates for itself, and fall short of a few of those dictated by its opponent. Since no two paradigms leave all the same problems unsolved, paradigm debates always involve the question: Which problems is it more significant to have solved? In the final analysis, this involves a question of values that lie outside of normal science altogether. It is this recourse to external criteria that most obviously makes paradigm debates revolutionary..

X - Revolutions as Changes of World View.

During scientific revolutions, scientists see new and different things when looking with familiar instruments in places they have looked before. Familiar objects are seen in a different light and joined by unfamiliar ones as well. Scientists see new things when looking at old objects. In a sense, after a revolution, scientists are responding to a different world.

Why does a shift in view occur? Genius? Flashes of intuition? Sure. Because different scientists interpret their observations differently? No. Observations are themselves nearly always different. Observations are conducted within a paradigmatic framework, so the interpretative enterprise can only articulate a paradigm, not correct it. Because of factors embedded in the nature of human perception and retinal impression? No doubt, but our knowledge is simply not yet advanced enough on this matter. Changes in definitional conventions? No. Because the existing paradigm fails to fit? Always. Because of a change in the relation between the scientist's manipulations and the paradigm or between the manipulations and their concrete results? You bet. It is hard to make nature fit a paradigm.

XI - The Invisibility of Revolutions.

Because paradigm shifts are generally viewed not as revolutions but as additions to scientific knowledge, and because the history of the field is represented in the new textbooks that accompany a new paradigm, a scientific revolution seems invisible.

The image of creative scientific activity is largely created by a field's textbooks. Textbooks are the pedagogic vehicles for the perpetuation of normal science. These texts become the authoritative source of the history of science. Both the layman's and the practitioner's knowledge of science is based on textbooks. A field's texts must be rewritten in the aftermath of a scientific revolution. Once rewritten, they inevitably disguise not only the role but the existence and significance of the revolutions that produced them. The resulting textbooks truncate the scientist's sense of his discipline's history and supply a substitute for what they eliminate. More often than not, they contain very little history at all. In the rewrite, earlier scientists are represented as having worked on the same set of fixed problems and in accordance with the same set of fixed canons that the most recent revolution and method has made seem scientific. Why dignify what science's best and most persistent efforts have made it possible to discard?

The historical reconstruction of previous paradigms and theorists in scientific textbooks make the history of science look linear or cumulative, a tendency that even affects scientists looking back at their own research . These misconstructions render revolutions invisible. They also work to deny revolutions as a function. Science textbooks present the inaccurate view that science has reached its present state by a series of individual discoveries and inventions that, when gathered together, constitute the modern body of technical knowledge - the addition of bricks to a building. This piecemeal-discovered facts approach of a textbook presentation illustrates the pattern of historical mistakes that misleads both students and laymen about the nature of the scientific enterprise. More than any other single aspect of science, the textbook has determined our image of the nature of science and of the role of discovery and invention in its advance.

XII - The Resolution of Revolutions.

How do the proponents of a competing paradigm convert the entire profession or the relevant subgroup to their way of seeing science and the world? What causes a group to abandon one tradition of normal research in favour of another?

Scientific revolutions come about when one paradigm displaces another after a period of paradigm-testing that occurs only after persistent failure to solve a noteworthy puzzle has given rise to crisis. This process is analogous to natural selection: one theory becomes the most viable among the actual alternatives in a particular historical situation.

What is the process by which a new candidate for paradigm replaces its predecessor? At the start, a new candidate for paradigm may have few supporters (and the motives of the supporters may be suspect). If the supporters are competent, they will improve the paradigm, explore its possibilities, and show what it would be like to belong to the community guided by it. For the paradigm destined to win, the number and strength of the persuasive arguments in its favour will increase. As more and more scientists are converted, exploration increases. The number of experiments, instruments, articles, and books based on the paradigm will multiply. More scientists, convinced of the new view's fruitfulness, will adopt the new mode of practising normal science, until only a few elderly hold-outs remain. And we cannot say that they are (or were) wrong. Perhaps the scientist who continues to resist after the whole profession has been converted has ipso facto ceased to be a scientist.

XIII - Progress Through Revolutions.

In the face of the arguments previously made, why does science progress, how does it progress, and what is the nature of its progress?

To a very great extent, the term science is reserved for fields that do progress in obvious ways. But does a field make progress because it is a science, or is it a science because it makes progress? Normal science progresses because the enterprise shares certain salient characteristics, Members of a mature scientific community work from a single paradigm or from a closely related set. Very rarely do different scientific communities investigate the same problems. The result of successful creative work is progress.

Even if we argue that a field does not make progress, that does not mean that an individual school or discipline within that field does not. The man who argues that philosophy has made no progress emphasises that there are still Aristotelians, not that Aristotelianism has failed to progress. It is only during periods of normal science that progress seems both obvious and assured. In part, this progress is in the eye of the beholder. The absence of competing paradigms that question each other's aims and standards makes the progress of a normal-scientific community far easier to see. The acceptance of a paradigm frees the community from the need to constantly re-examine its first principles and foundational assumptions. Members of the community can concentrate on the subtlest and most esoteric of the phenomena that concern it. Because scientists work only for an audience of colleagues, an audience that shares values and beliefs, a single set of standards can be taken for granted. Unlike in other disciplines, the scientist need not select problems because they urgently need solution and without regard for the tools available to solve them. The social scientists tend to defend their choice of a research problem chiefly in terms of the social importance of achieving a solution. Which group would one then expect to solve problems at a more rapid rate? .

We may have to relinquish the notion, explicit or implicit, that changes of paradigm carry scientists and those who learn from them closer and closer to the truth . The developmental process described by Kuhn is a process of evolution from primitive beginnings. It is a process whose successive stages are characterised by an increasingly detailed and refined understanding of nature. This is not a process of evolution toward anything. Important questions arise. Must there be a goal set by nature in advance? Does it really help to imagine that there is some one full, objective, true account of nature? Is the proper measure of scientific achievement the extent to which it brings us closer to an ultimate goal? The analogy that relates the evolution of organisms to the evolution of scientific ideas "is nearly perfect" . The resolution of revolutions is the selection by conflict within the scientific community of the fittest way to practice future science. The net result of a sequence of such revolutionary selections, separated by period of normal research, is the wonderfully adapted set of instruments we call modern scientific knowledge. Successive stages in that developmental process are marked by an increase in articulation and specialisation. The process occurs without benefit of a set goal and without benefit of any permanent fixed scientific truth. What must the world be like in order than man may know it?