Paradigms, Citations, and Maps of Science: A Personal History

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Can maps of science tell us anything about paradigms? The author reviews his earlier work on this question, including Kuhn's reaction to it. Kuhn's view of the role of bibliometrics differs substantially from the kinds of reinterpretations of paradigms that information scientists are currently advocating. But these reinterpretations are necessary if his theory will ever be empirically tested, and further progress is to be made in understanding the growth of scientific knowledge. A new Web tool is discussed that highlights rapidly changing specialties that may lead to new ways of monitoring revolutionary change in real time. It is suggested that revolutionary and normal science be seen as extremes on a continuum of rates of change rather than, as Kuhn originally asserted, as an all or none proposition.

History of Science and Bibliometric Structure

The deeper you delve into the history of any topic the more you begin to see the connections between ideas, people, and institutions captured in the historical context. I began thinking about mapping science as part of a project to document the history of nuclear physics (Small, 1972). The project was conducted at the American Institute of Physics, and its goal was to describe nuclear physics and its evolution through time. I began wondering if methods could be found for graphically showing the evolution of historical connections within the field. As a doctoral candidate in the history of science, I was deeply influenced by Thomas Kuhn's "structural" view of scientific development (Kuhn, 1970), and mapping a field seemed somehow related to his concept of the paradigm.

Unfortunately, Kuhn never gave us clear empirical guidelines for defining exactly what a paradigm was (Masterman, 1970; Shapere, 1964), and his discussion remained mostly on a philosophic level. In the well-known Postscript to the second edition of his book (Kuhn, 1970), Kuhn emphasized that a paradigm was shared by members of a specialized community. But he did not explain how, given such a community, we could go about finding the paradigm shared by its members. Kuhn described paradigmatic elements variously as theories, models, equations, tacit knowledge, beliefs, values, and "exemplary past achievements," or exemplars, all components of his "disciplinary matrix." He did note that specialty communities could be identified by studying communication patterns, such as referencing in the literature or informal communications among scientists, but was content to leave the details to others. Because of this vagueness in definition, paradigms have remained mostly a philosophic construct, and for most historians as elusive as unicorns.

For the nuclear physics project I first tried to map the intellectual landscape of leading researchers in the field such as Ernest Rutherford. By an intensive reading of their papers, I constructed diagrams of the evolving models of the atomic nucleus. Ideas or hypotheses were represented as nodes that were linked together if they were part of a supporting argument or assertion. I could then show how these networks evolved with each successive paper, and the introduction of new concepts such as the neutron. More recently Paul Thagard (1992) developed a theory of "explanatory coherence" which is a more fully elaborated theory of what I was attempting. Thagard models each theory as a network of hypotheses, evidence, etc. that either support or contradict each other. The computation of the winning theory is implemented in an AI program called ECHO. His model stresses that within any historical context the only guide we have is to find the most consistent collection of facts and theoretical statements.

I soon realized, however, that if I continued coding the scientific literature in this way I would have to retire before my work was completed. Therefore, I turned to a simpler kind of analysis focusing on bibliographic elements in papers that might function as concept surrogates. To explore the possibilities I coded all nuclear physics papers in the *Physical Review* for the 1920s and 1930s, recording authors, key words, affiliations, classification headings, and a sample of cited references for each paper.

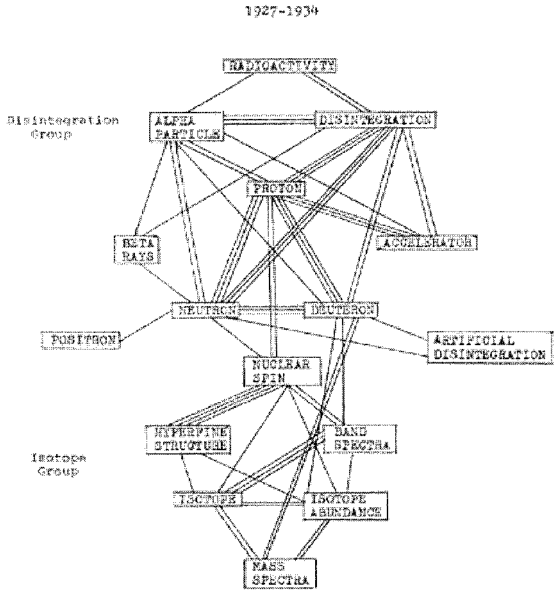

FIG. 1. Map showing key words in nuclear physics papers from 1927–1934 linked by co-usage. The number of lines connecting the words indicates frequency of co-use, for example, four lines indicated 40 or more co-uses. Word pairs links having fewer than five co-uses are not indicated. The map shows the important role played by the neutron and deuteron particles in uniting different subdisciplines within nuclear physics.

From these data I created what we would now call co-word (Callon, Law, & Rip, 1986), coclassification, and cocitation maps for different slices of time. I reasoned that if words appeared together, or cooccurred, in multiple papers, then the community of authors probably saw some logical connection between them (Fig. 1). The same held true for the coassignment of classification headings, and jointly cited papers and authors (Small, 1972). All these cooccurrence graphs increased in complexity as the field grew and reflected the emergence of key discoveries such as the neutron and particle accelerators.

Cocitation Work at ISI

After joining ISI in 1972, my first thought was to continue my co-word analyses using ISI's *Permuterm Index*® that was part of the *Science Citation Index* (*SCI*®) (Garfield, 1984). But encountering homograph problems in this multidisciplinary database I returned to my ideas on reference cooccurrence, and to my surprise the patterns in the SCI were much stronger than what I had seen in my historical samples (Small, 1973). The highly cited documents seemed to have special symbolic significance, standing for specific discoveries, methods, or ideas that were shared by the citing authors, what I later called "concept symbols" (Small, 1978). Strong cocitation links between highly cited papers were also highly focused and precise. This was getting closer to the logical interplay of ideas I had originally sought. I later realized that citations were more potent concept symbols than words because high citation rate reflected, however imperfectly, peer recognition (Kaplan, 1965).

After initial experiments with the printed SCI, I resolved to automate the cocitation clustering process with a full SCI database. Kuhn (1977) had also suggested that exemplars would form clusters, which he illustrated by gaggles of geese, swans, and ducks. It was about this time that I met Belver Griffith, professor of information science at Drexel University, and we embarked on an analysis of a quarterly SCI file (Small & Griffith, 1974). My goal was to apply the cocitation methodology across all the sciences so that the full structure could be viewed on a single map. Derek Price (1986) referred to this as the war map of science, and he envisioned a room where government bureaucrats would monitor a large display of the scientific terrain planning their next maneuver.

To identify research areas by cocitation analysis, a threshold was first set to select highly cited papers. Sampling highly cited papers evenly across disciplines turned out to be a key step in constructing comprehensive maps of science. One solution was fractional citation counting (Small & Sweeney, 1985), and more recently, in the Essential Science Indicators, discipline specific thresholds. After the formation of cocitation links, a cluster analysis was carried out.

To obtain a mapping, however, we needed a method for arranging the clustered documents in two dimensions in a way that would reflect their degree of relatedness, what we would now call visualization. This might reveal the fine structure of specialties and aid in interpretation. Belver Griffith was familiar with a technique developed by Joseph Kruskal (1964) at Bell Labs called multidimensional scaling, and this became our preferred procedure. Today, a much broader range of ordination techniques is available from pathfinder networks (Schvaneveldt, 1990), latent semantic indexing (Deerwester, Dumais, Furnas, & Morar, 1990), Kohonen (2001) self-organizing maps, simulated annealing (Boyack, Wylie, & Davidson, 2002), and triangulation (Small, 1999a).

The research front work at ISI in the 1970s and 1980s revolved around an annual process of cocitation clustering for each full year of the SCI. To look for changes, each year was layered on the previous year using common highly cited papers as markers. I was on the look out for what Kuhn had called "microrevolutions" at the specialty level, in contrast to the macrorevolutions his theory is usually associated with. Because revolution implies more than mere discovery, such small-scale shifts in specialized areas would differ from simple discovery-driven growth.

Bibliometric Definition of a Paradigm

Kuhn's reaction to our initial papers on the cocitation structure of science was one of puzzlement. He wondered why we had focused on highly cited papers and authors, rather than defining the total community of researchers involved with the topic, representing the complete paradigm-sharing community. Any notion that highly cited papers might stand for exemplars or other paradigmatic constructs was not on his radar. Presumably, Kuhn saw bibliometric methods only as a means of performing a social inventory of a specialty, not as way to define the paradigm itself. Therefore, it is unlikely that Kuhn would have accepted any of our bibliometric reinterpretations of his theory.

It is clear that any use of citation data can only be an approximation to Kuhn's original multifaceted notion of paradigm. Quite possibly, however, highly cited documents are as close to his exemplars ("exemplary past achievements") as information science can get. He had stated that exemplars would include " . . . at least some of the technical problem-solutions found in the periodical literature . . ." (Kuhn, 1970, p. 187). The best that we can expect from bibliometric models is a partial and imperfect reflection, as Griffith (1979) would say, a "faulty mirror" of science.

Several years later I specified in more detail the relationship between the cocitation representation of specialties and Kuhn's paradigms, and this relationship was in my view linguistic (Small, 1980). Although Kuhn had maintained that paradigms could not be adequately described in words (Shapere, 1964), a verbal reconstruction seemed not only necessary but also potentially useful. I showed how individual cocitation links could be translated into scientific assertions, and a cluster of such links viewed as an interlocking network of statements. Texts of the citing papers were analyzed near the point of citation, the so-called cocitation context, and a consensual pattern of language usage across multiple citing authors was teased out. Hopefully translating paradigm-clusters into scientific discourse would ease the way to a new kind of specialized information service (Garfield, 1983).

Thus, the essential requirements of paradigm hunting were a means of pulling together the communally shared concept surrogates, and a means of translating them into scientific discourse. Clearly, citation data provided a unique mechanism for establishing consensual connections, whether through Garfield's (Garfield, Shar, & Torpie, 1964) historiographs, Kessler's (1963) bibliographic coupling (Schiminovich, 1971), or cocitation (Small, 1973). Clustering and ordination of these relationships allowed the analysis to move beyond pair-wise linkages to an aggregate structural and thematic analysis.

Specialty Dynamics

The study of specialty dynamics proved to be more complex than originally expected due to the changeable nature of research fronts from year to year. New papers continually appeared in the clusters as their citation and cocitation rates increased, and old papers dropped out. This seemed part of the natural evolution and obsolescence of knowledge, but much more fluid that Kuhn's "normal science." The dynamic nature of research fronts also made science maps less stable from year to year.

Comparisons of annual maps showed considerable low-level change with, however, continuity in certain large-scale structural features such as the relative locations of major disciplines (Small, 1993). A methodology evolved for aggregating individual research fronts into a hierarchical structure (Small & Sweeney, 1985), using the stronger cocitation links to form specialties and the weaker ones to tie specialties together into an interdisciplinary network. The weak interdisciplinary ties were the glue that held the structure together. Despite the high turnover of documents, disciplines hung together in a fragile web.

A rival theory to Kuhn's for explaining the changeable nature of specialties is to regard scientific papers as falsifiable hypotheses in the tradition of Karl Popper (1972). Citations then have the character of hypotheses or conjectures, recursively embedded in other hypotheses. Citation-hypotheses are shuffled in and out, varied, and added to according to their state of falsification. Despite the vulnerability of all hypotheses, which together could resemble a house of cards, the structure would gain strength and stability by virtue of numerous weak dependencies among them. This could account for the seeming paradox that scientific consensus is extremely fluid, yet at the same time the overall structure of disciplines remains fairly stable.

Pathways through Science

Studying the nature of pathways through science (Small, 1999b) can suggest mechanisms for specialty growth. It is possible to travel systematically, document by document, from a topic such as sociology to another topic such as astrophysics, in a series of logical steps traversing multiple disciplines. Links within specialties often involve incremental extensions of knowledge based on shared themes, while interdisciplinary links involve imaginative leaps based more subtly on analogy. The exploration of these pathways raises intriguing philosophical questions about how different knowledge domains are connected, what E.O. Wilson (1998) calls the consilience of science.

To illustrate an intraspecialty pathway we use a cluster of four papers on the storage of hydrogen gas in carbon nanotubes (Fig. 2). This research is concerned with finding a safe means of storing hydrogen gas for use in fuel cells. Each paper is represented as a list of themes. Solid lines indicate strong cocitation links and dotted lines indicate some of the shared themes. Among the set of papers, some themes are shared while others are unique to a specific document. In this example, overarching themes are "single-walled carbon nanotubes" and "hydrogen storage." Some unique themes are "quantum effects," "helium desorption," and "phase transition." Authors, of course, have embedded these themes in arguments and assertions. Combining these arguments across the set of papers creates a network of discourse with the themes as nodes.

Such collective networks of discourse are, in my view, what give science its strong epistemologic position. It is by no means certain that carbon nanotubes will successfully

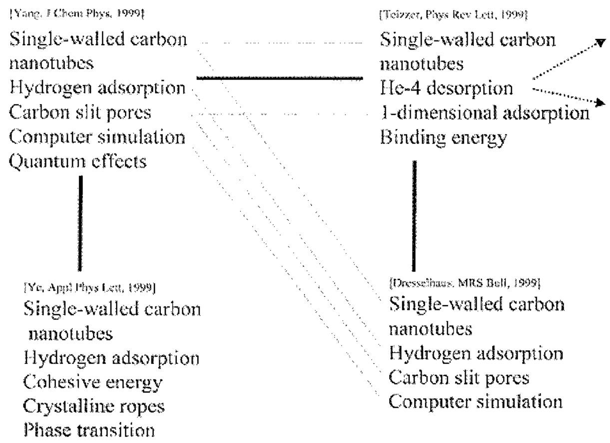

FIG. 2. Schematic diagram of a cocitation cluster of four papers on hydrogen storage in carbon nanotubes. Each paper is represented by a list of themes. Solid lines indicate strong cocitation links; dotted lines indicate shared themes, only some of which are shown for illustrative purposes. Two arrows indicate the point of attachment of two papers on the rare gas adsorption in carbon nanotubes in the following time period (see Table 1 for list of papers).

solve the hydrogen storage problem for fuel cell technology. The research is controversial and could unravel, like cold fusion did, based on faulty measurements (Baughman, Zakhidov, & De Heert, 2002). But the collective and interconnected nature of the research area, with its supporting network of arguments, gives it an initial credibility beyond what might be granted to an isolated idea.

The unique themes in this network, in addition, may act as receptors or points of attachment for new papers that can expand the scope of the specialty. So, for example, in the next time period the paper on "helium desorption" became a point of attachment for two additional papers, one on xenon adsorption and the other more generally on rare gas adsorption in carbon nanotubes (see items 1 and 3 in Table 1). The connection is thus based on analogy, helium and xenon both being rare gases.

Essential Science Indicators

The hydrogen storage example was drawn from a new web product for studying the structure of science called ISI Essential Science Indicators (ESI). ESI is an integrated compilation of data on highly cited research in the sciences, incorporating research fronts as one of its features. Fronts are obtained by a cocitation analysis of highly cited papers in 22 fields using a 5-year moving compilation of citation data, updated every 2 months. The frequency of updating offers a dynamic view of the evolution of specialties, making possible the identification of new, rapidly growing or changing areas by comparing each bimonthly cluster against its predecessor in the prior period. A sampling of these results is presented in an editorial site linked to the product called "Special Topics" (www.esi-topics.com). The Special Topics web page highlights research fronts that are either new to the system, called "emerging research fronts," or have grown rapidly from one period to the next, called "fast moving fronts."

An "emerging research front" is a cluster consisting of highly cited papers that did not appear in any front in the prior period. "Fast moving fronts," on the other hand, are

TABLE 1. Cluster of 15 papers on hydrogen storage in carbon nanotubes (order is by a breadth-first search of the minimal spanning tree for the cluster).

1. Kuznetsova, A., Yates, J.T., Liu, J., & Smalley, R.E. (2000). Physical adsorption of xenon in open single walled carbon nanotubes: Observation of a quasi-one-dimensional confined Xe phase. Journal of Chemistry & Physics, 112(21), 9590–9598.
2. Teizer, W., Hallock, R.B., Dujardin, E., & Ebbesen, T.W. (1999). He-4 desorption from single wall carbon nanotube bundles: A one-dimensional adsorbate. Phys. Rev. Lett., 82(26), 5305–5308 [original cluster].
3. Stan, G., & Cole, M.W. (1998). Low coverage adsorption in cylindrical pores. Surface Science, 395(2–3), 280–291.
4. Stan, G., & Cole, M.W. (1998). Hydrogen adsorption in nanotubes. Journal of Low Temperatures Physics, 110(1–2), 539–544.
5. Darkrim, F., & Levesque, D. (1998). Monte Carlo simulations of hydrogen adsorption in single-walled carbon nanotubes. Journal of Chemistry & Physics, 109(12), 4981–4984.
6. Wang, Q.Y., & Johnson, J.K. (1999). Molecular simulation of hydrogen adsorption in single-walled carbon nanotubes and idealized carbon slit pores. Journal of Chemistry & Physics, 110(1), 577–586, 1999 [original cluster].
7. Hynek, S., Fuller, W., & Bentley, J. (1997). Hydrogen storage by carbon sorption. International Journal of Hydrogen Energies, 22(6), 601–610.
8. Ye, Y., Ahn, C.C., Witham, C., Fultz, B., Liu, J., Rinzler, A.G., Colbert, D., Smith, K.A., & Smalley, R.E. (1999). Hydrogen adsorption and cohesive energy of single-walled carbon nanotubes. Applied Physics Letter, 74(16), 2307–2309 [original cluster].
9. Nutzenadel, C., Zuttel, A., Chartouni, D., & Schlapbach, I. (1999). Electrochemical storage of hydrogen in nanotube materials. Electrochem Solid State Letter, 2(1), 30–32.
10. Dresselhaus, M.S., Williams, K.A., & Eklund, P.C. (1999). Hydrogen adsorption in carbon materials. MRS Bulletin, 24(11), 45–50 [original cluster].
11. Lee, S.M., & Lee, Y.H. (2000). Hydrogen storage in single-walled carbon nanotubes. Applied Physics Letter, 76(20), 2877–2879.
12. Williams, K.A., & Eklund, P.C. (2000). Monte Carlo simulations of H-2 physisorption in finite-diameter carbon nanotube ropes. Chemical & Physics Letter 320(3–4), 352–358.
13. Lee, S.M., Park, K.S., Choi, Y.C., Park, Y.S., Bok, J.M., Bae, D.J., Nahm, K.S., Choi, Y.G., Yu, S.C., Kim, N.G., Frauenheim, T., & Lee, Y.H. (2000). Hydrogen adsorption and storage in carbon nanotubes. Synthethetic Metal, 113(3), 209–216.
14. Wu, X.B., Chen, P., Lin, J., & Tan, K.L. (2000). Hydrogen uptake by carbon nanotubes. International Journal of Hydrogen Energies 25(3), 261–265.
15. Gupta, B.K., & Srivastava, O.N. (2000). Synthesis and hydrogenation behaviour of graphitic nanofibres. International Journal of Hydrogen Energies 25(9), 825–830.

TABLE 2. Research front dynamics.

	Number of fronts
New fronts	521 (12.2%)
Fronts increasing in size	515 (12.1%)
Fronts with no change in size	2,311 (54.1%)
Fronts decreasing in size	923 (21.6%)
Total fronts	4,270 (100%)

clusters having a rapid rate of increase in the number of highly cited papers they contain. In measuring the growth of a front we take into account patterns of coalescence or merging that have occurred from period to period by comparing the sizes of the current clusters with the sum of the sizes of all previous, contributing clusters. To increase in size the current front must be larger than the sum of all prior contributing fronts.

For example, in the second bimonthly period of 2002, ESI identified 4,270 fronts. Table 2 shows how these fronts can be categorized as new, increasing, stable, and decreasing based on a comparison with data for the prior period. The larger number of decreasing than increasing fronts is due to the more restrictive way of measuring growth by taking mergers into account.

For example, the carbon nanotube front was first observed as an emerging front in early 2001 when it consisted of a cluster of four highly cited papers. By the end of 2001 the front had grown to 15 papers, including the four initial papers (Table 1). By February of 2002 the size of the front increased to 23 highly cited papers. Thus, an emerging front in early 2001 became a fast moving front the following year.

Microrevolutions

Following Kuhn, revolutionary change should involve a replacement of one set of documents by another, indicating an overthrow of an old viewpoint, and not merely the addition of new documents. At the same time there must be some degree of continuity with the prior field. Otherwise, we would see it as simply an emerging field.

Detecting revolutionary change in a specialty involves measuring the replacement rate within the paradigm, which is approximated by the turnover in the set of highly cited documents. A high rate of turnover, or low stability, would indicate revolutionary change, while a low turnover, and high stability, would indicate normal science. Following the criterion used in an earlier study (Small, 1977), we define a "stability index" as the number of continuing highly cited papers divided by the size of the union of the prior and subsequent fronts. We look for a small "stability index" (0.2 or less) where the sizes of the initial and subsequent fronts are more than twice the number of continuing documents.

To simplify the detection of revolutionary change we focus only on those fronts not engaged in merges or splits, what might be called fronts with patterns of simple continuation. Examining all such cases from ESI from the first two update periods of 2002 we see how rare microrevolutionary change is on the time scale of 2 months for this restricted class of cases. Of the 4,270 fronts in the second period, 3,250 (76%) are what we have called "simple continuations." In most of these cases, the front papers have not changed at all from period to period (Table 3).

Applying the criteria that the stability index be 0.2 or less and the front size for both the prior and subsequent clusters be more than double the size of the number of continuing highly cited papers, only one front out of the 3,250 cases would qualify as a potential microrevolution. It is an area in applied mathematics on the topic of "chromatic polynomials" consisting of three highly cited papers in each period with one continuing paper. Weakening the criterion to more than 1.5 times the number of continuing papers yields four fronts as potential revolutionary cases. The largest of these contains six highly cited papers and is a topic in environmental science concerning "platinum group metals as environmental contaminants."

By extending the series from two to three consecutive bimonthly sets of fronts, we begin to see the importance of time in our revolution hunting. Comparing the sixth bimonthly period of 2001 to the first two bimonthlies of 2002 we identify 2,274 simple continuations. The mean stability index of the first against the third bimonthly set, skipping the second, is 0.76 versus a mean of 0.90 for the second against the third. Thus, as the width of the time window widens, the less the stability, and the higher the document turnover. Using the same criteria as before, instead of one potential microrevolution case, we now have 18. Of these the two fronts having the lowest stability deal with "thin polyelectrolyte multilayer films" and "nanocrystalline titanium dioxide solar cells," both areas in materials science.

At this point we do not have sufficient evidence to say whether any of these cases represents a true microrevolution. Of course, expanding our search to fronts with mergers and splits, or adopting a different criterion of revolutionary change, might change the picture. But it does appear that the number of putative revolutions will increase as the time horizon expands.

Redefining Kuhn

Perhaps it is time to reformulate Kuhn's theory of revolutionary change in science in more continuous terms, as Toulmin (1972) and later Hull (1988) suggested. Research front data indicate that there is an ongoing process of birth and renewal in scientific specialties. New areas continue to

TABLE 3. Fronts with simple continuation.

	Number of fronts
Fronts increasing in size	468 (14.4%)
Fronts with no change in size	2,272 (69.9%)
Fronts decreasing in size	510 (15.7%)
Total simple continuation fronts	3,250 (100%)

form at a steady rate. Some of these new areas fall by the wayside, while others persist and continue to evolve. The continuing ones either add new papers incrementally, sprout new lobes as Chen, Cribbin, Macredie, and Morar (2002) have shown in their case studies, or in rare cases old lobes are replaced with new ones, as in the case of collagen (Small, 1977). Revolutionary change may only be an artifact of time scale: the longer a field persists the more likely it is that a total morphing of its document set will occur, as new ideas edge out old ones. We notice only the cases where change is sudden and dramatic, not those in which change is continuous and gradual. Most revolutionary change in this model would be evolutionary, and part of the natural process of renewal and obsolescence of knowledge. One test of this would be to present scientists with the documents in a current research front and its ancestor front several years back and ask whether they see the change as normal or revolutionary. Most, in my view, would see the change as revolutionary.

Despite the pervasive influence of Kuhn's theory across the sciences and social sciences, it remains untested and controversial. There is a need to get beyond the rhetoric and translate this theory into testable form. This translation can and should proceed using a variety of tools and units of analysis, for example, scientific terminology, indexing terms, cited documents, cited authors, questionnaires, and surveys. Aggregating these units of analysis, by clustering or ordination, should then lead to measurements of rates of change. Eventually, the extremes of normal and revolutionary science that Kuhn described may survive only as idealized polar opposites; what remains is a continuum of rates of change from slow to rapid, as a function of the time window. It will be up to the information scientists and bibliometricians to extend and elaborate Kuhn's theory in these new directions.

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