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THE PAPER TRAILS OF SCHOLARSHIP: MAPPING THE LITERATURE OF GENETICS[1]

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Multidimensional scaling and cluster analysis of the co-citation patterns of forty-nine authors are used to investigate changes in the structure of *Drosophila* genetics literature over the years 1974–78 and 1979–83. This literature is shown to consist of a central set of author clusters representing classical genetics, surrounded by more specialized research clusters: developmental genetics, molecular genetics, neurogenetics, and population genetics. The co-cited author structure illustrates the general intellectual historical development of *Drosophila* genetics and is extremely stable over time. Visible changes in research patterns include the increased prominence of neurogenetics and the cross-cluster migration of individual authors. The overall stability derives from (1) the greater citation visibility and inertia of the author's oeuvre as the unit of analysis (in contrast to individual documents) and (2) temporal characteristics of the journal article as a formal archival record of research activity. Interpretations and hypotheses must take these into account.

The scholarly journal article is a major source of information regarding structure and change in scientific literatures and associated changes in the intellectual, social, or cognitive structure of scientific specialties. For many sociologists of science, the research focus has been on the changing structure of communication patterns and social relationships associated with intellectual progress [1]. Content analysts have discussed aspects of the rhetoric of scholarly discourse [2, 3]. Bibliometric studies examine the changing structure of scientific fields through the analysis of the literature produced by the scholars themselves. Citation analysis has been used frequently to describe various characteristics of subject literatures and the fields producing them [4, 5]. Two measures of document linkage through cited references—bibliographic coupling [6, 7] and co-citation

[8, 9]—have been used to investigate subject literature networks. Both measures are based on the relationships between source papers and the citations they contain; bibliographic coupling analysis focuses on the (static) linkage of *source* documents by the number of shared references, while co-citation analysis focuses on the (dynamic) relationships among *cited* documents based on frequency of their co-occurrence in source documents. These changing linkages are, in effect, paper trails illustrating the changing patterns of scholarly activity and intellectual structure.

The bibliometric approach to investigation of the structure of scientific specialties has been criticized on many grounds [5, 10, 11]. The journal article is generally characterized as the public archival record of validated scientific knowledge [12]. However, although the journal represents the major formal channel of communication in the sciences, informal communication may play a much more important role in information transfer at the research front in specific disciplines or specialties [13, 14]. Such decisions as coauthor name sequence and citation choices may reflect individual or community behavioral norms, and the citations themselves may serve a variety of functions [15–17]. The citation data in *Science Citation Index*® and *Social Sciences Citation Index*® (and their online counterparts) are somewhat problematic. Even so, there is good evidence that the structure of the formal literature is congruent with the intellectual and social structure of the field producing it [18–22].

The co-citation structure of subject literatures has been studied at two different levels of generality.[3] *Document* co-citation studies use as the unit of analysis the individually cited reference, usually (but not always) a scholarly journal article. Literature structure is represented by clusters of frequently co-cited documents. Henry Small, Belver Griffith, and others have shown that these clusters represent narrow research specializations in the sciences and social sciences. These document clusters are linked at higher levels as broader field and discipline aggregations [23–25]. Changing patterns of research activity, shifts in intellectual perspective, and so forth, can be observed in the changes within document clusters and in the emergence and disappearance, coalescing and splitting, of clusters [20, 26].

Author co-citation studies provide a more generalized view of literature structure. Conceptually, the author's name represents his or her cited oeuvre—an aggregation of single or coauthored documents.[4] Literature structure is demonstrated at this higher level of generality by interlinked clusters of frequently co-cited authors. Author clusters have been shown to represent broad research specializations, theory groups, or temporal associations [27–29]. As in the finer-grained co-cited document studies, changes in intellectual activity recorded in the journal literature are evidenced by inter- and intracluster change over time [21, 22, 30].

This is the third of a series of articles reporting the results of research [21] that uses co-cited author data to examine (1) the congruence between literature structure and perceived intellectual structure and change in two scientific fields (macroeconomics and *Drosophila* genetics) and (2) the congruence between literature structure and perceived intellectual structure in each field. Previous articles dealt with the changing structure of macroeconomics [28] and the validity of co-cited author mapping as a representation of intellectual structure [22]. This paper examines various aspects of the formal journal literature as a source of information concerning the changing structure of a subject field. The discussion focuses on the results of a co-cited author mapping of the literature of *Drosophila* genetics over two successive time periods. Methods of data collection and analysis are presented very briefly, and the reader is referred to the earlier reports for substantive discussions of these points.

Methods

In co-cited author mapping, the scholarly universe is represented by a set of names of relatively prominent authors representing a wide variety of scholarly activity in a given field. The raw data collected are the frequencies of co-occurrence of all pairs of authors' names in the reference lists of source papers published over a specified time period. This can be accomplished using standard bibliographic retrieval techniques to retrieve co-citation data from appropriate online databases. An overall measure of similarity of co-citation pattern can be calculated for each author across the entire set, and this measure is used as input to computer-based mapping and clustering programs.

The results are generally displayed as two-dimensional maps of points representing authors' names, with clusters of authors who are linked by similar patterns of co-citation identified and labeled. Figures 1 and 2 are examples of such a map. The position of each genetics author is represented by a dot; the placement of these dots reflects the similarities of the authors' co-citation patterns. The more similar two authors are, the more closely their positions will be placed on the map, and authors with many links to others are generally placed near the center of the map [31].

Clusters of similar authors are indicated by solid lines. The cluster labels reflect the shared focus of the authors' research. The spatial orientation of authors and author clusters in the maps—indicated by the map's axes—illustrate underlying dimensions of research orientation or scholarly style in the field being studied.[5]

In the study of *Drosophila* genetics, authors' names were drawn from a multivolume collection of review articles [33, 34] and from discussions with knowledgeable geneticists. A set of forty-nine authors' names were successfully searched on *SCISEARCH®*, the online version of *Science Citation Index*, via DIALOG. The input command CR=HALL JC? AND CR=BENZER S? will, for example, retrieve all source papers citing any work by J. C. Hall together with any work by S. Benzer—with the constraint imposed by the database that citation access is only to authors listed as first or sole author of the cited works. Thus Hall's name represents some portion of his entire cited oeuvre. The authors' names act as paired descriptors, generally restricting the retrieval set to papers on neurogenetics.[6]

Using accession-number ranges to subdivide DIALOG files, co-citation data were collected from source papers published in 1974–78 and 1979–83 (to April). In each time period, the raw co-citation data for all authors were assembled in a square matrix representing a co-citation profile for each author across the entire set. A product-moment correlation was calculated as an overall measure of profile similarity between each pair of authors. The interauthor correlations were used as input to a multidimensional scaling program [36] and a clustering program [37].[7] The correlation serves as an inverse distance measure; the more similar the profiles of two authors, the larger the positive correlation and the more closely these authors are linked in the mapping and clustering. The results are shown as two-dimensional maps of author clusters in figures 1 and 2.

Results

Figure 1 shows a map of *Drosophila* genetics from the literature published in 1974–78. *Drosophila* genetics, as represented by this set of forty-nine authors, consists of a central core of interlocked and closely associated research areas focusing on the classical genetics of the fruit fly. Surrounding this central area are other distinctive research areas linked to the core. These correspond to the three different research paths in modern genetics—developmental genetics, molecular genetics, and the genetics of populations [39]. The author clusters in the center of the map represent the classical approach to *Drosophila* genetics, and authors in this area share a great many cross-cluster ties. The complexity of this central portion arises from the influence of early contributors (for example, T. H. Morgan and his students) as well as the diverse contributions (primarily methodological) of more contemporary authors (for example, Dan Lindsley, Laurence Sandler, and David Suzuki).

All the authors in the developmental genetics cluster have studied some aspect of adult or larval developmental genetics of *Drosophila*. Four of the five authors clustered in molecular genetics represent the first generation of researchers in the molecular structure and function of *Drosophila* genes; Thomas Maniatis, a molecular biologist, is connected through his research in gene cloning techniques and the creation of a "library" of *Drosophila* genes. In chromosome puffing, H. J. Becker and Michael Ashburner are linked through research on a particular phenomenon of chromosome structure, but Thomas C. Kaufman's connection with this problem and these authors is unclear. Authors in the remaining two clusters, population genetics and evolution and population behavior genetics, are concerned with populations of interbreeding organisms. In this time period, these eight authors are separated into two clusters representing (1) a broad range of research in population and evolutionary genetics and (2) a more focused concern with behavioral variation in populations.

The horizontal axis points to two different methodological approaches to research in *Drosophila* genetics: the biometrical or statistical approach characteristic of population studies versus the experimental genetics of individuals represented by the major network of clusters. This choice of methodology affects the kinds of questions asked, the research methods used, and the criteria for evaluation of research results. The vertical axis represents a continuum of research interests across *Drosophila* genetics from primarily genetic questions at the molecular and cellular level (at the upper end) to questions dealing primarily with the genetic control of biological processes (at the lower end).

The map of the later time period, 1979–83 (fig. 2), shows little change, and, *at this level of analysis*, it appears that *Drosophila* genetics has undergone little intellectual "reorganization." There is still a set of interlocked clusters (the core) emphasizing, in this later period, a slightly different set of interauthor associations.[8] Molecular, developmental, and population genetics remain distinct research specializations, and the overall spatial arrangement of the clusters is essentially the same. The major change is associated with the increased "visibility" of neurogenetics.

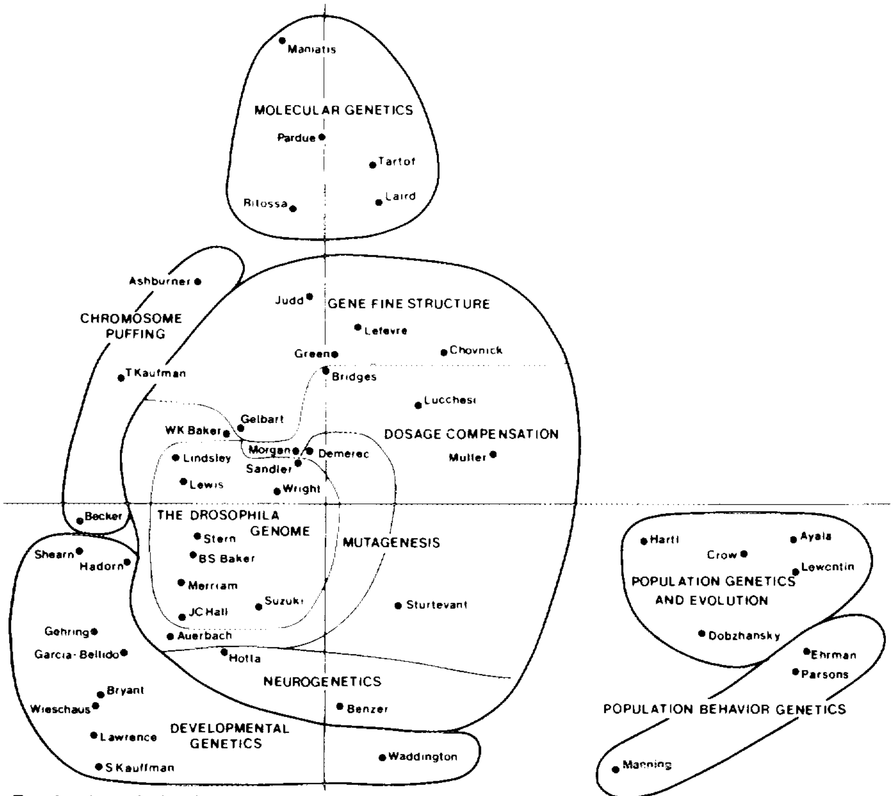

FIG. 1.—A co-cited author map of *Drosophila* genetics, 1974–78

In figure 1, this cluster was part of the core. Since the mid- to late 1970s, research in neurogenetics and single gene behavior genetics has grown. Hall's scientific career parallels this change—from doctoral research on problems of meiosis in Sandler's laboratory to postdoctoral work with Benzer (neurogenetics) and current research in neuro- and behavior genetics. Examination of the two maps shows that his newer work is recognized and cited, resulting in his relocation and association with other neurogenetics researchers.

The chromosome puffing cluster has disintegrated, and cluster boundaries have shifted to include these authors. Ashburner's highly cited 1979 paper on RNA synthesis links his work with Francisco Ritossa and other authors in the molecular genetics cluster.[9]

Cluster boundaries have also shifted in the population genetics area. Population behavior genetics is no longer distinct at this clustering level. James Crow and Daniel Hartl are distinguished in this time period by their work on segregation distortion (a genetic phenomenon observable in population data and studied using classical and molecular techniques). In addition, C. H. Waddington's models of development have apparently become less relevant to developmental genetics, and his ties to evolutionary genetics are emphasized.

Discussion

In a study of the structure of a scientific literature and its field, authors, as units of analysis, have a stability, a visibility, and an inertia that individual documents generally lack. These characteristics are likely to reflect field-specific patterns of communication and research activity, and production and use of formal journal literature. The value of these characteristics depends on the nature of the investigation and the questions being asked.

The Visibility of the Author as Oeuvre

The author's name, representing a (partial) co-cited oeuvre, may include a set of highly cited documents, each replacing the other in reference lists over time. The author remains visible, with no indication of the shifting identity of the oeuvre. Small-scale alterations in research patterns and concomitant structural changes are consequently not visible. Document co-citation analysis is capable of showing finer changes in intellectual structure [20, 26]. Alternatively, the author's oeuvre may consist of a range of relatively substitutable documents, each not cited sufficiently to be observable as individual documents but, as a set, maintaining the author at a visible level over a considerable period of time. This type of visibility is not possible in document co-citation analysis since (by definition) no individual document in the author's oeuvre is cited sufficiently to "make the cut." Fields with relatively low publication frequency and growth rate are accessible by using the author, rather than the document, as the unit of analysis.

Citation Inertia

Inertia (resistance to movement or persistence in a cluster) may result from the continuing citation of an extremely useful contribution even after the author has changed research problems. Documents retain a life of their own. Methodological contributions are more likely to provide inertia to an author's oeuvre than conceptual, theoretical contributions [20]. Reviews, in those areas of science that produce and value them, may also influence citation patterns until replaced by more current work. Scientific scholarship is cumulative, and the citation of a review replaces a large number of individual citations to earlier seminal work. As source documents, the reviews may create "artifacts" insofar as an author co-citation map is presumed to illustrate current research associations.[10] A detailed analysis of source papers and citation counts may be necessary to evaluate the influence of inertia-producing contributions.

Temporal Characteristics of Citation Data

Studies of scientific communication and research activity have shown that a time lag of more than a year may occur between the first "formal" communication of research results (at a public seminar) and the publishing of these results in a refereed scholarly journal. It may take an additional period of one or two years for this work to be cited in other articles by the same or other authors [40]. All studies using citation data are ultimately historical analyses of past research and publishing activity; this is not a defect so much as simply a characteristic of these data and their source. The timeliness of the data reflect the rate of literature turnover and may be dependent on the availability and popularity of weekly journals, letters journals, and the like. Interviews with citing scholars [21] can produce hypotheses to be tested in future mappings. In genetics, these include predicted cluster reassignment of authors based on their post-1980 research interests and cluster relocations reflecting the incorporation of molecular genetics techniques across most of the other research areas.

Another temporal aspect of journal use and citation choice potentially visible in co-cited author maps is the shifting of citation function associated with the aging of the subject literature. The decreased use of older volumes of scientific journals is a phenomenon well known to serials librarians and special librarians with limited storage space. Though there is some debate over the existence of journal "obsolescence" as opposed to decreasing "use," analysis of citation data has shown that citations to older volumes of journals tend to drop at a rate disproportionate to the increase in citable material [41]. Different venues of scholarship may "age" their respective literatures at different rates, and distinctions between "research front" and "archival" use of the literature are often made [42, 43]. Highly cited individual documents also have distinctive aging patterns [44], and it is not unlikely that, as time passes, citations to individual oeuvres may shift in character from research-relevant citations to those merely honorific, resulting in the linkage of authors in clusters as founders or "grand old men." Interview data show that geneticists are well aware of the contributions and historical importance of authors such as Morgan and his students (Milislav Demerec, Alfred Sturtevant, Curt Stern, Calvin Bridges, and Theodosius Dobzhansky) in the "Fly Room" at Columbia University in the early part of this century. However, the maps suggest that these early researchers are still being cited for the research relevance of their contributions rather than simply as early historical figures.

Mapping Developmental History

In co-citation mapping, the paper trails documenting knowledge utilization are likely to illustrate the past development history of the field. Small and Diana Crane [25] discussed (document) cluster networks in terms of Michael Mulkay's "branching model" of the development of new research specialties—a "center-periphery" model of knowledge development. Mulkay [45, p. 518] illustrates this scenario of problem area and specialty development in radio astronomy as a proliferation of new research areas from older ones, with research paths dividing over time. Were the time axis collapsed, fields following this developmental scenario would appear as a network of older core areas surrounded by newer peripheral areas that draw from the older research. Small

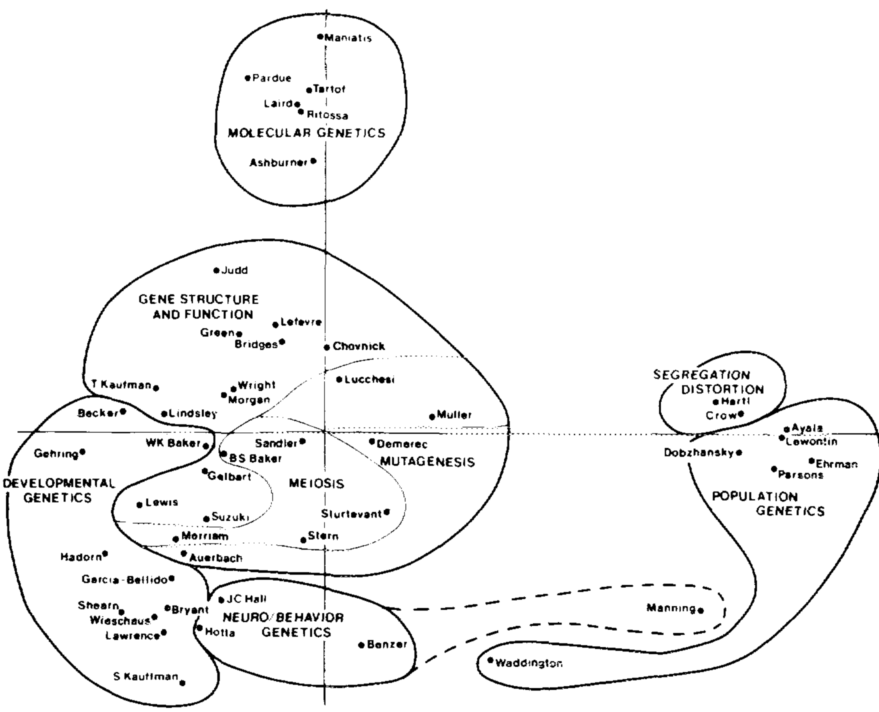

FIG. 2.—A co-cited author map of *Drosophila* genetics, 1979–83

and Crane suggest that "nodal clusters" in their data represent the (older) core areas that are providing ideas used in the adjacent peripheral areas. A similar map configuration, a more tightly linked central set of (author) clusters surrounded by more distinct peripheral clusters, was described for decision sciences [46].

The maps in figures 1 and 2 suggest that the history of *Drosophila* genetics (as defined by these data) fits Mulkay's scenario. In both maps, *Drosophila* genetics exhibits a noticeable "center-periphery" arrangement, with Morgan and the majority of the Columbia Fly Room scientists in the network of core clusters. Surrounding this core are more distinctly specialized author clusters. The early workers in the field were necessarily generalists—dealing with a range of questions that later researchers have taken up on a more individual basis. It is not accurate, however, to equate knowledge production and utilization uniquely with central and peripheral cluster positions, as the model and Small and Crane suggest. Molecular genetics, for instance, is increasingly providing both analytical techniques and substantive knowledge used by researchers throughout the major research network—knowledge transfer from periphery to center.[11]

Tracing Scholarly Migration

Journal articles are the documented results of research activity and an individual researcher may change problems and research areas over the course of his or her career, migrating across specialty or disciplinary boundaries. Several sociologists of science [45, 47, 48] have presented scenarios that emphasize the role of migration in the development of scientific specialties. The visibility of scholarly migration in co-citation data depends on a sequence of factors: (1) the author must, in fact, either change research topics or reemphasize one line of research at the expense of an earlier one; (2) the new area must be sufficiently active, in terms of publication, for any cited authors to be visible (this is an advantage of authors over documents as units of analysis); (3) the contributions of the "immigrant" must be recognized and cited; (4) citations to the author's new work, and co-citation with new colleagues, must be sufficient to outweigh or override those to his or her previous contributions (to overcome inertia) and produce new visible linkages.

While the author's oeuvre is potentially more visible than any individual paper, noticeable inertia is created by continuing citations to important previous contributions (conceptual as well as methodological) and by the necessity for this four-step cascade of activity to occur. This ensures the overwhelming stability of author co-citation maps and suggests that any visible change is likely to reflect major changes in intellectual activity.

Two types of migration can be seen in the genetics maps. Hall, as noted earlier, moved from an association with research in chromosome mechanics to research in the new and growing specialty of neuro- and behavior genetics. This type of movement can be termed "active migration" since it resulted from an active decision on the part of the author to change fields. Ashburner's reassignment from chromosome puffing to molecular genetics may be another case. Other authors' movements and reassignments appear to represent, at least in part, a reemphasis of a different portion of the author's previously published oeuvre. This also results in the establishment of a new set of co-citation linkages concomitant with changes in the field and can be called "passive migration." Waddington's cluster reassignment was, according to informants, the result of the decreasing relevance (and citation) of his models of development to contemporary developmental genetics. Becker's movement into developmental genetics (from chromosome puffing) may also represent "passive migration." Active and passive migration cannot be distinguished on the basis of co-citation data alone, but should be interpretable based on subsequent investigation.

Summary

The scientific journal article, as a validated public record of research activity, provides much grist for the bibliometrician's mill. Co-citation studies are one productive tool for the study of structure and change in subject literatures and scientific specialties. The use of authors' names as surrogates for sets of cited documents has certain advantages over the use of individual works in these investigations. Methods of data collection and analysis are readily available to anyone with access to computer terminals and standard statistical packages. Investigation is not restricted to those "hot" fields with high rates of publication and citation. Intellectual co-cited author structure appears to be extremely stable over time—representing the overall historical development of the field—and changes in research patterns can be traced against this background.

The results of any bibliometric analysis, including co-citation studies, must be interpreted in the light of the general and field-specific properties of the journal article as a data source. Individual behavior choices and community norms may determine the degree to which the citation data are a current mirror of scholarly activity. Information provided by citing scholars (or other sources of insight into the particular field of study) is useful both in interpretation of the co-citation maps and clusters and in the construction of hypotheses to be tested in subsequent investigations.

FOOTNOTES

1. I thank the members of my dissertation committee for their support and encouragement during this research. Data collection was supported by a research award from Sigma chapter, Beta Phi Mu, Drexel University, and by the College of Information Studies. Presentation of this research in the doctoral forum at the annual meeting of the American Society for Information Science, October 23, 1985, Las Vegas, was supported in part by an award from the Special Interest Group on Education for Information Science. I thank Julie Hurd and the members of the committee for this opportunity. Elizabeth Aversa provided useful comments on an earlier draft of this paper, but all errors of fact and interpretation are, of course, my responsibility.
2. College of Information Studies, Drexel University, Philadelphia, Pennsylvania 19104.
3. The majority of studies examining relationships among scholarly journals have relied on cross-citation data; that is, what journals are *cited in* journal A and what journals contain articles *citing* journal A (see, for example, [4]). These studies are not considered further here.
4. In practice, the completeness of this oeuvre depends on the information provided by the database and reflects the publishing habits of the author.
5. In previous author co-citation studies, one dimension has generally represented some aspect of scholarly style and the second a subject orientation; see discussion in [21] and [32].
6. See [35] for a discussion of these retrieval techniques and [21, appendix A] for a detailed presentation of DIALOG commands for author co-citation retrieval.
7. JOHNSN is a program based on Johnson's clustering algorithms [38]. The "smallest diameter" approach was used here.
8. The slight differences in several cluster labels reflect these shifts in interauthor associations.
9. Other aspects of more recent work in molecular *Drosophila* genetics (for example, transposable elements) are not well represented since sufficient data on additional "second generation" molecular authors could not be collected for both time periods.
10. Document co-citation analysis is not immune to this problem. "Hypercited" methods papers, such as O. H. Lowry's paper on protein determination, may be such strong "linkers" across research areas that they must be removed from the data set to let finer structural features emerge in the clustering [24].
11. Not all author co-citation maps illustrate Mulkay's model. Both macroeconomics maps [28] and current macroeconomic texts suggest that the intellectual history of macroeconomics has been essentially linear rather than radial—a continuing series of attempts to respond to certain basic problems and to predict future developments.

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