How Does Science Progress?
A Statistical Approach to Postmodern Theories of Knowledge

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Abstract:

Thomas Kuhn's *Structure of Scientific Revolutions* (1962) proposes a theory of knowledge—science undergoes periodic paradigm shifts—that has been interpreted to mean that there is no 'truth' in science. To test this theory, I construct "citation trees," where each node is a paper connected to all the papers it cites and the papers that cite it. Just as in evolutionary biology where a species tree has branches that get sparse or discontinued during periods of mass extinctions, I look for similar events in a citation tree. Using ISI data, I construct geology, linguistics, and literary criticism trees dating from 2001 back to 1945, 1956, and 1975 respectively. I also use the NBER Patent Citation database from 1975-1999. Markov clustering algorithms marking death of "bushes" indicate linguistics and geology are qualitatively different from literary criticism, where statistical "extinctions" occur often, contrary to the constructionist claim that all forms of discourse accumulate similarly. Paradigm shifts incommensurate enough to cause mass extinctions do not appear to have occurred in linguistics, geology, or patent citations but literary criticism may have had a paradigm shift in 1990.

Thomas Kuhn's *Structure of Scientific Revolutions* (1962) proposes a theory of knowledge—science undergoes periodic paradigm shifts—that has been hotly debated by historians, philosophers, and sociologists.[iiiii] After Kuhn, postmodernists have interpreted paradigm shifts and their incommensurability to mean that there is no 'truth' in science, that science is only a reflection of its historical socio-cultural environment.[iv] Others believe science accumulates slowly by logical steps based on prior knowledge rather than radical reformulations.[v] Previous tests of the theory, or of any historical theory of science, tend to be archival, comparing rhetoric, subjective, or anecdotal.[vi] Recent statistical tests consider the age at which scientists generate breakthrough innovations to see if the age profile undergoes sharp transitions during paradigm shifts.[viiviii]

Understanding the laws governing science and knowledge accumulation has long been a goal of social scientists.[ixx] Economic historians and growth economists have asked why some societies are technologically creative.[xi] The present economics of science literature, however, with a few exceptions[xii], mainly studies the economic incentives that scientists face.[xiiixiv] I focus on testing Kuhn's paradigm shifts hypothesis[xv] because it appears to be basis of postmodernists' constructionist claims on science, a controversy that has spilled onto the popular press.[xvixviixviii] To say paradigms are incommensurate means concepts and theories in different paradigms are mutually unintelligible and hence not objectively comparable.[xix] Whether knowledge accumulation experiences periodic extinctions also tests a recent theoretical model of knowledge accumulation that distinguishes between recombinant growth and branching growth, which has a computable probability of extinction.[xxxxi]

I construct a citation 'tree' (formally, a graph) where each node is a paper connected to all the papers it cites and the papers that cite it. Then, just as in evolutionary biology where a species tree has branches that get sparse or chopped off during times of mass extinctions, I look for similar events in citation trees (Figure 1).[xxiixxiii] Patent citations have been used as measure of creative destruction in economic growth.[xxivxxv] Network analysis traces intellectual networks among academics across generations.[xxvixxviixxviii] I build on these two literatures in my

methodology. The first method clusters disciplines into bushes, implementing the MCL (Markov cluster) algorithm[xxixxxx] and then marks the time at which bushes end (the year of the last article in the bush). Since natural clusters (bushes) in a graph are characterized by the presence of many edges between members of that cluster, the number of paths between two arbitrary nodes within this cluster should be high relative to node pairs lying in different natural clusters. In other words, random walk on the graph will infrequently go from one natural cluster to another, based on graph transition probability estimates. The MCL algorithm uses a bootstrapping procedure to compute probabilities of random walks through the use of stochastic matrices. The second method treats each citation as a fossil imprint. The idea is that the impact of each paper is marked in subsequent citations, so the time of extinction is the last time it is cited. I look for periods of extinctions rising above a background rate of extinction. I do not distinguish between positive and negative citations since the vast majority of citations in scientific journals are positive.[xxxi]

I compare linguistics, geology, and comparative literature trees. Chomsky and plate tectonics are commonly held to have triggered paradigm shifts in linguistics and geology, whereas both participants and observers would agree that comparative literature (literary criticism) is not a "science." If these trees are identical in a statistically meaningful way, then this would be informative: either no paradigm shifts with any degree of incommensurability can be detected or 'fads' in the non-sciences look identical to purported paradigm shifts in the sciences, testing the constructionist claim that all forms of knowledge accumulate similarly. If only the linguistics and geology trees look like they undergo paradigm shifts, this may help determine reasonable parameters for speed and quantities of extinction (i.e. how fast is fast and how many is catastrophic) when examining larger trees, such as physics.

Using databases from the ISI Web of Science, I construct citation trees that date from 2001 back until 1945 for geology (constituting 10,458 articles[xxxii]), 1956 for linguistics (constituting 9,249 articles[xxxiii]), and 1975 for comparative literature (constituting 6,892 articles[xxxiv]). I restrict to top journals selected by academics in the field to reduce the possibility of the periphery dominating the center; to test the sensitivity of the results to this restriction, I also obtain a 70% sample (42 of 59 journals[xxxv]), constituting 49,972 articles[xxxvi], for linguistics. Patent citation data was downloaded from NBER, constituting 2,088,795 patents from 1975 to 1999.[xxxvii]

The results for linguistics, geology, and comparative literature are displayed in Figures 2A-2C. The first striking contrast can be seen here. Comparative literature (Figure 2A) shows a roughly constant rate of extinction across time with the exception of a sharp spike at 1990. Geology (Figure 2B) and linguistics (Figure 2C) are very different. Conversations within bushes continue until the very end of the timeframe, where censoring sharply increases the number of extinctions. With fewer journals, there may be fewer connections between ideas even when they really should exist. This gap in the record might artificially increase the rate of random extinctions. Using the linguistics 70% sample (Figure 2D), and keeping cluster size constant, the results are qualitatively the same.

I next investigate whether the findings are robust to changing cluster size. The smaller the cluster threshold given to the MCL algorithm, the finer it partitions the graph. Increasing cluster size for linguistics does not affect the qualitative results (Figure 3A). Decreasing the cluster size, on the other hand, makes the extinction profile much more noisy. Conversations are not allowed to continue across time much, so their extinctions will track more closely the number of articles (Figure 3B). The results for geology are the same (not shown). Since shrinking the

clusters in linguistics forced the dialogues to end arbitrarily, I consider whether the medium cluster size is too small and increasing the cluster size for comparative literature might qualitatively change the results, but it does not (Figure 4A). Only when the cluster size is shrunk, does the extinction profile change dramatically and track more closely with the number of articles (Figure 4B).

The broad picture for linguistics, geology, comparative literature, and patents[xxxviii] using the second method is similar. In comparative literature, extinctions occur at a relatively constant rate (Figure 5A), whereas in linguistics, geology, and patent citations, extinctions occur massively at the end of the time period (Figures 5B-5D), despite a declining number of geology articles.

These results suggest that only literary criticism has paradigm shifts so incommensurate that ideas cannot converse across two different paradigms and that comparative literature may have a break with its past in 1990.[xxxix] The ratio of citations to articles is lower in comparative literature and extinctions are common. Remarkably, no sharp break could be detected in the linguistics data around 1964, when Chomsky introduced a purported paradigm shift, or anytime else. Conversations within branches continue until the end of the time period. Geology displays the same pattern as linguistics, despite a level or decreasing number of articles. Patent citations display the same pattern as geology and linguistics, suggesting that scientific fields may be distinguishable from non-scientific ones.

Definitive proof of progress in science need not rest on the existence of paradigm shifts or its lack. Yet given the lay and academic controversy surrounding whether science is merely magic or religion, equal in 'truth' status to any other discourse, I am unable to quantitatively detect paradigm shifts in scientific fields. I interpret this to mean that scientific ideas are able to communicate across purported paradigm shifts, in contrast to the notion of incommensurability introduced by Kuhn. Other scientists have reached this conclusion through archival analysis.[xlxli] This finding is also more consistent with evolutionary epistemology[xlii], which predicts multiple paradigms coexisting and competing, and Popper, who claimed science proceeds via gradual evolution.

One possible explanation for the difference for literary criticism is the field's heavy reliance on books, which could introduce a bias in that articles cite outside the database and hence conversations would appear to end when they have not. This is akin to shrinking the number of clusters, however, and the reliance on books does not really explain why the distinctive pattern in literary criticism and sharp spike at 1990 remains when the cluster size is increased. Moreover, an empirical study of obsolescence of knowledge in different academic disciplines finds that English is remarkable in having very little obsolescence because people cite articles further in the past than in scientific disciplines.[xliii] This fact makes the detection of paradigm shifts all the more surprising in comparative literature as compared to linguistics and geology.

Future research using this framework can investigate whether new branches arise when a branch splits in two or from cross-fertilization across several branches, whether likelihood of intellectual impact is a function of distance between the old ideas that are combined[xliv], when interdisciplinary work is productive[xlv] with the goal of optimizing scientific progress. The method can also be adopted for other academic discourses to see what fields progress more like science and which do not. Studying the incommensurability of perspectives is of broad interest. The interchangeability of perspectives reappears in many moral philosophies.[xlvi] Understanding why scientific discourse has commensurability of perspectives might help policy-makers attain

that commensurability or interchangeability of perspectives for political and religious discourse as well, a source of present conflict.

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[ii] Kuhn, Thomas S. (1962), *The Structure of Scientific Revolutions*, Chicago: U. Chicago Press.

[iii] Kuhn, Thomas S. (2000), *The Road Since Structure*, Chicago: U. Chicago Press.

[iv] Rorty, Richard (1986), "Science as Solidarity," reprinted in *The American Intellectual Tradition Volume II: 1865 to the Present*, David A. Hollinger and Charles Capper, eds. (2001) Oxford: Oxford U. Press, pp. 452-462.

[v] Sokal, Alan, "A Physicist Experiments with Cultural Studies," *Lingua Franca*, July 1996.

[vi] Crane, Diane (1972), *Invisible Colleges*, Chicago: U. Chicago Press.

[vii] Jones, Ben (forthcoming), "Age and Great Invention," *Review of Economics and Statistics*.

[viii] Jones, Ben (forthcoming), "The Burden of Knowledge and the Death of the Renaissance Man: Is Innovation Getting Harder?" *Review of Economic Studies*.

[ix] Stigler, George (1982), *The Economist as Preacher*, Chicago: U. Chicago Press.

[x] Rosenberg, Nathan (1993), "George Stigler: Adam Smith's Best Friend," *Journal of Political Economy*, 101(5), pp. 833-848.

[xi] Mokyr, Joel (1990), *The Lever of Riches*, New York: Oxford U. Press.

[xii] Brock, William A. and Steven N. Durlauf (1999), "A Formal Model of Theory Choice in Science," *Economic Theory*, 14, pp. 113-130.

[xiii] Stephan, Paula E. (1996), "The Economics of Science," *Journal of Economic Literature*, 34, 1199-1235.

[xiv] Dasgupta, Partha and Paul A. David (1994), "Towards a New Economics of Science," *Research Policy*, 23, pp. 487-521.

[xv] A paradigm is usually defined as not just a set of axioms or theories but a discipline's entire worldview: the methods, the concepts, the appropriate way of asking questions. Kuhn's leading example is the contrast between Aristotelian physics and Newtonian physics, where "vacuum" is a meaningful concept in the latter paradigm but meaningless in the former. In Aristotelian physics, matter does not exist separately from qualities (like position or solidity). So wherever there's position, there is matter, i.e. there is matter everywhere in space; the void, space without matter, is a notion impossible to Aristotle.

[xvi] "The Foundations of Science," *The Economist*, October 25, 2001.

[xvii] "Coming to Blows Over How Valid Science Really Is," *New York Times*, July 22, 2001.

[xviii] "A Philosopher's Call to End All Paradigms," *The Chronicle of Higher Education*, September 15, 2000.

[xix] Rorty, Richard (1986), "Science as Solidarity," reprinted in *The American Intellectual Tradition Volume II: 1865 to the Present*, David A. Hollinger and Charles Capper, eds. (2001) Oxford: Oxford U. Press, pp. 452-462.

[xx] Weitzman, Martin (1998), "Recombinant Growth," *Quarterly Journal of Economics*, 113(2), pp. 331-360.

[xxi] Criticality theorem for branching processes. Heyde, C. C. and E. Seneta (1972), "The Simple Branching Process, a Turning Point Test and a Fundamental Identity: A Historical Note on I. J. Beinayme," *Biometrika*, 59, pp. 680-683.

[xxii] Futuyma, Douglas (1997), *Evolutionary Biology*, Sunderland, MA: Sinauer Associates, Inc.

[xxiii] Marshall, Charles R. and Peter D. Ward (1996), "Sudden and Gradual Molluscan Extinctions in the Latest Cretaceous of Western European Tethys," *Science*, 274, pp. 1360-1363.

[xxiv] Caballero, Ricardo J. and Adam B. Jaffe (1993), "How High are the Giants' Shoulders: An Empirical Assessment of Knowledge Spillovers and Creative Destruction in a Model of Economic Growth," in *NBER Macroeconomics Annual*, Cambridge: MIT Press.

[xxv] Griliches, Zvi (1990), "Patent Statistics as Economic Indicators: A Survey," *Journal of Economic Literature*, 28(4), pp. 1661-1707.

[xxvi] Wasserman, S. and K. Faust (1994), *Social Network Analysis*, Cambridge: Cambridge U. Press.

[xxvii] Collins, Randall (1998), *The Sociology of Philosophies, A Global Theory of Intellectual Change*, Cambridge: Belknap Press of Harvard U. Press.

[xxviii] Brock, William A. and Steven N. Durlauf. (2000), "Interactions-Based Models," in *Handbook of Econometrics 5*, James Heckman and Edward Leamer, eds., Holland: Elsevier Science.

[xxix] Van Dongen, Stijn (2000), *Graph Clustering by Flow Simulation*, Dutch National Research Institute for Mathematics and Computer Science, Ph.D. thesis.
[xxx] Enright, A. J., S. Van Dongen, and C. A. Ouzounis. (2002) "An efficient algorithm for large-scale detection of protein families." *Nucleic Acids Research*, vol. 30, no. 7, 1575-1584.
[xxxi] Negative citations are on the order of 3% or less of total citations. Hull, David (1988), *Science as a Process, An Evolutionary Account of the Social and Conceptual Development of Science*, Chicago: U. Chicago Press.
[xxxii] Journal of Geology, Geological Society of America Bulletin
[xxxiii] Anthropological Linguistics, Journal of Linguistics, Language, Lingua, Natural Language & Linguistic Theory
[xxxiv] PMLA-Publications of the Modern Language Association of America, Modern Philology, MLN-Modern Language Notes
[xxxv] 59 journals from Linguistic Society of America were available on ISI Web of Science.
[xxxvi] Anthropological Linguistics, Journal of Linguistics, Language, Lingua, Natural Language & Linguistic Theory, Acta Linguistica Academiae Scientiarum Hungaricae, American Speech, Applied Linguistics, Applied Psycholinguistics, Canadian Journal of Linguistics-Revue Canadienne de Linguistique, Cognitive Linguistics, Cognitive Science, Cognition, Computational Intelligence, Computational Linguistics, Folia Linguistica, German Life and Letters, Journal of Child Language, Journal of East Asian Linguistics, Journal of Language and Social Psychology, Journal of Literary Semantics, Journal of Memory and Language, Journal of Neurolinguistics, Journal of Phonetics, Language and Cognitive Processes, Language & Communication, Language and Speech, Language in Society, Language Learning, Linguistic Analysis, Linguistic Review, Linguistics, Linguistics and Philosophy, Mind & Language, Oceanic Linguistics, Semiotica, Studia Linguistica, Studies in Language, System, TESOL Quarterly, Theoretical Linguistics, Transactions of the Philological Society
[xxxvii] Hall, B. H., A. B. Jaffe, and M. Tratjenberg (2001). "The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools." NBER Working Paper 8498.
[xxxviii] I was unable to use the MCL algorithm on the patent data due to its size.
[xxxix] The break in 1990 is possibly due to the rise in popularity of deconstructionism (Derrida) or postcolonial studies.
[xl] Oreskes, Naomi (1999), *The Rejection of Continental Drift*, Oxford: Oxford U. Press.
[xli] Mayr, Ernst (1997), *This is Biology*, Cambridge: Belknap Press of Harvard U. Press.
[xlii] Hull, David (1988), Science as a Process, An Evolutionary Account of the Social and Conceptual Development of Science, Chicago: U. Chicago Press.
[xliii] McDowell, John M. (1982), "Obsolescence of Knowledge and Career Publication Profiles: Some Evidence of Differences among Fields in Costs of Interrupted Careers," *American Economic Review*, 1982, pp. 752-768.
[xliv] Jacobs, Jane (1970), *Economy of Cities*, New York: Vintage Books.
[xlv] Garber, Marjorie (2000), *Academic Instincts*, Princeton: Princeton U. Press.
[xlvi] E.g. Golden Rule, Spinoza's Viewpoint of Eternity, Hobbes's Social Contract, Rousseau and Locke, Kant's Categorical Imperative, and Rawl's Veil of Ignorance.

Figure 1

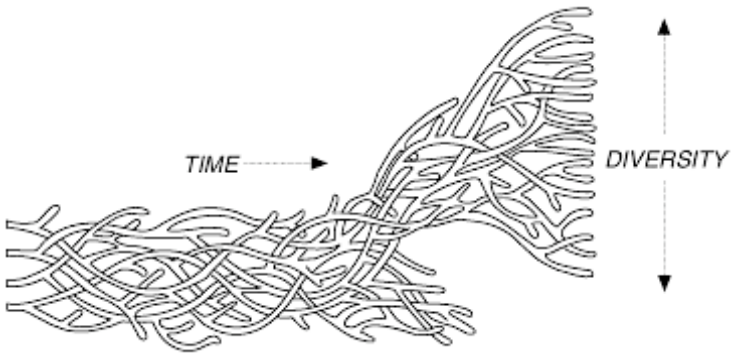

Figure 2A: Extinctions in Comparative Literature

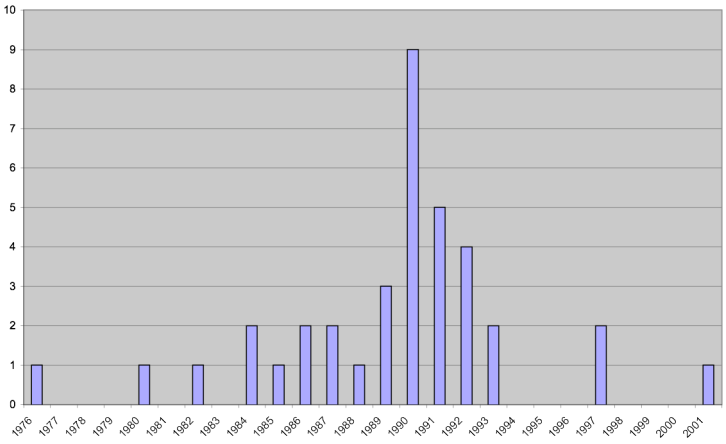

Figure 2B: Extinctions in Geology

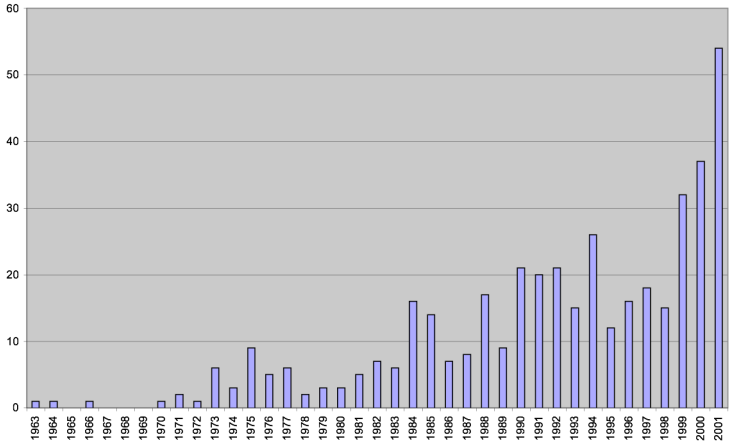

Figure 2C: Extinctions in Linguistics (5)

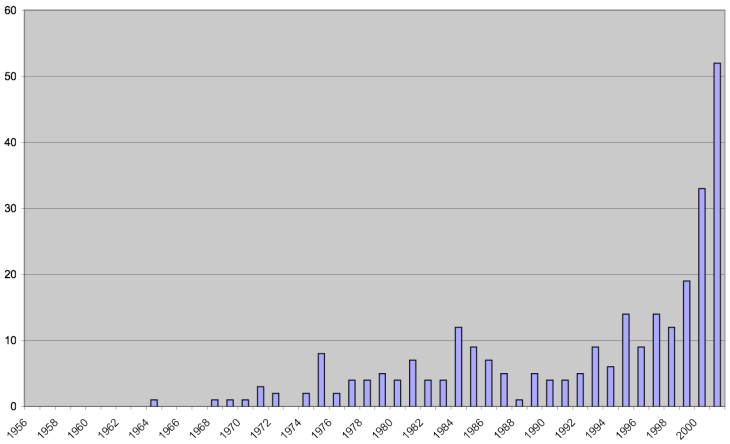

Figure 2D: Extinctions in Linguistics (70%)

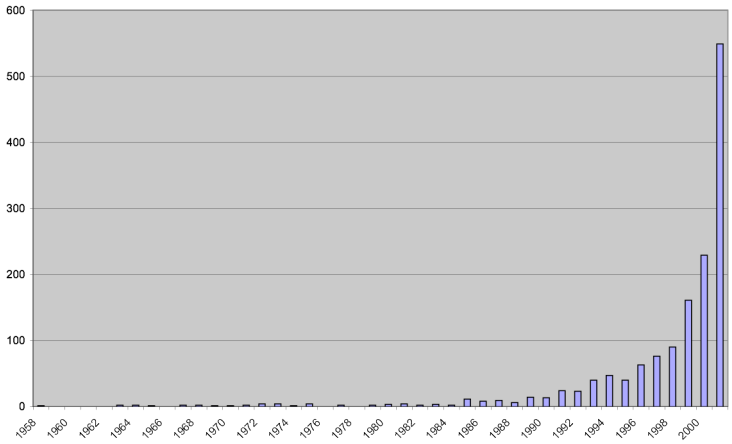

Figure 3A: Extinctions in Linguistics (5) (large clusters)

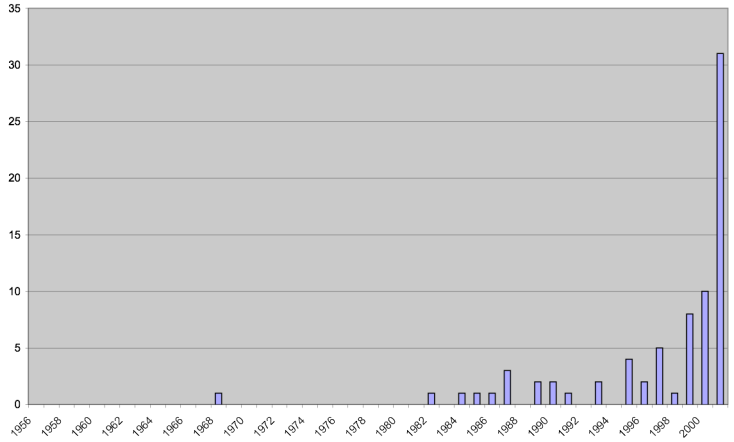

Figure 3B: Extinctions in Linguistics (5) (small clusters)

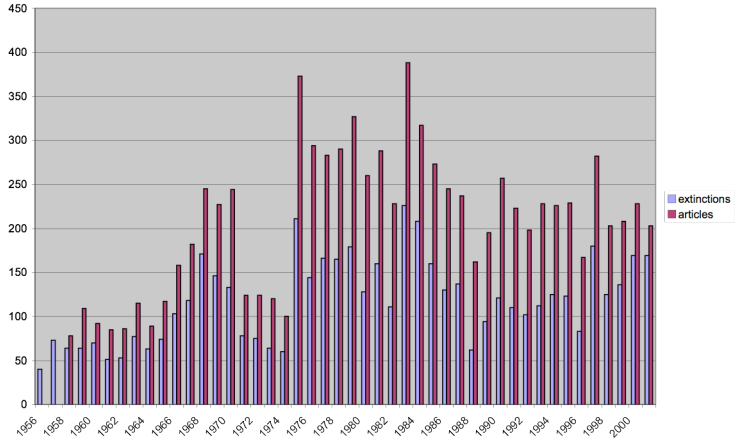

Figure 4A: Extinctions in Comparative Literature (large clusters)

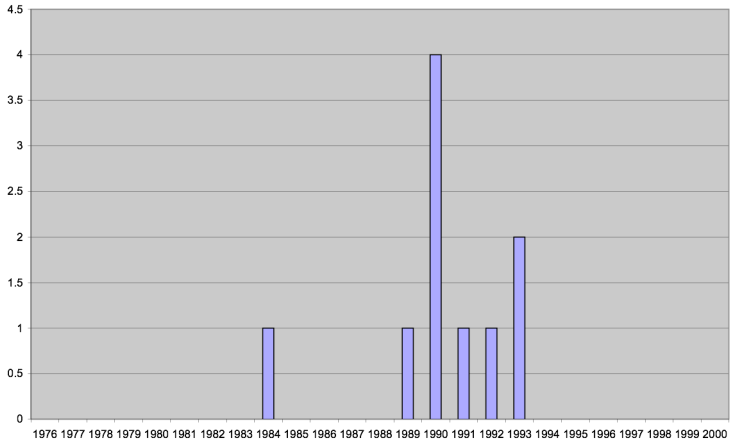

Figure 4B: Extinctions in Comparative Literature (small clusters)

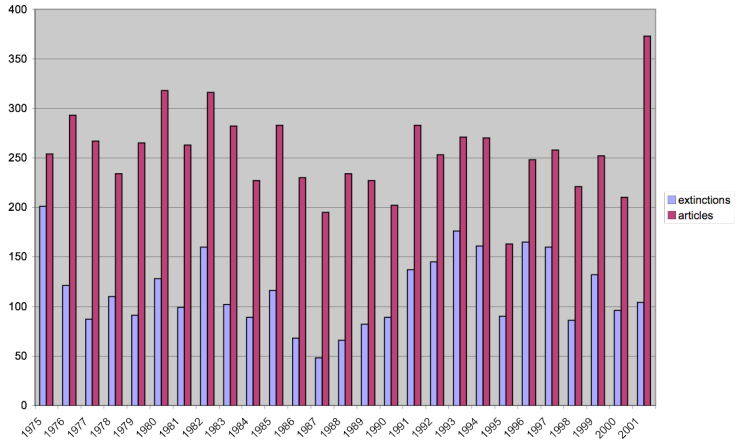

Figure 5A: Extinctions in Comparative Literature

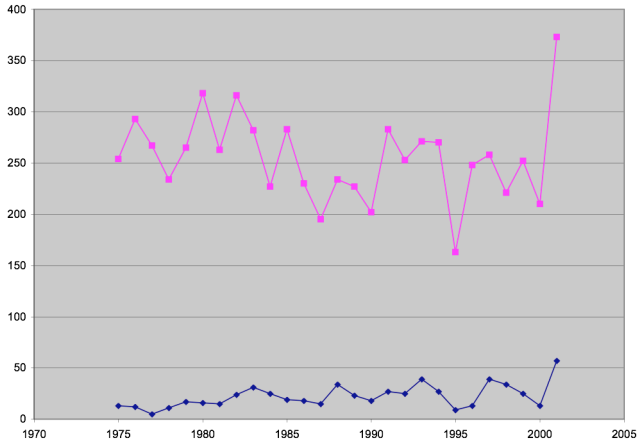

Figure 5B: Extinctions in Geology

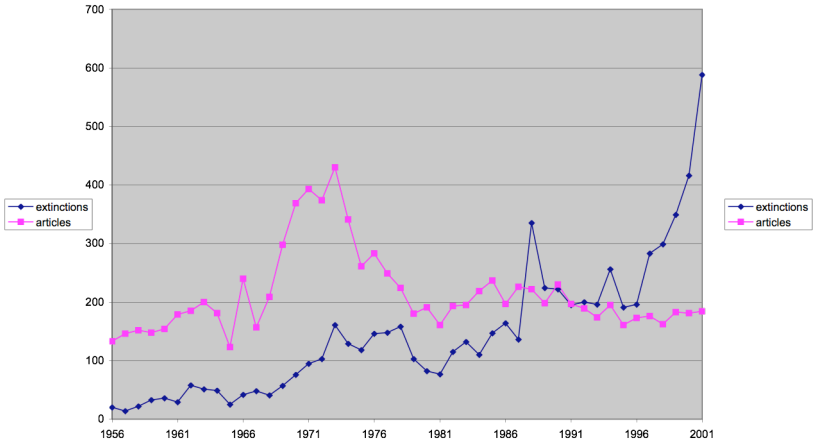

Figure 5C: Extinctions in Linguistics (70%)

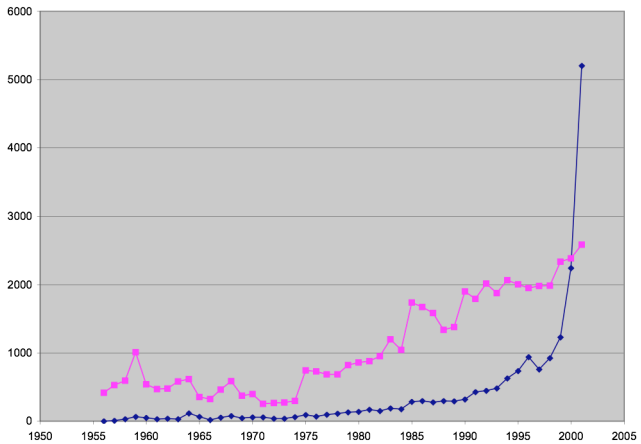

Figure 5D: Extinctions in Patent Citations