This article presents the theory behind modern evaluative bibliometric techniques at three levels. Policy applications, which characterizes the scientific and technological output of nations or regions; strategic analyses, which deals with articles and patents at the level of a university or company; and tactical analyses, which addresses questions concerning a single subject. The article explains the newer techniques that have been developed at each level, as well as the more important limitations.

BIBLIOMETRICS/THEORY, PRACTICE AND PROBLEMS

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Bibliometrics, and in particular evaluative bibliometrics, uses counts of publications, patents, and citations to develop science and technology performance indicators. These indicators measure scientific and technological accomplishment, and have been growing steadily in scope, complexity, and power since their formal introduction in the first *Science Indicators 1972* report (U.S. National Science Board 1973)..

The need for bibliometric indicators arises from the enormous growth in scientific and technological activity that has been occurring for centuries, and has now reached avalanche proportions. In his wonderful book *Little Science Big Science*, Derek Price (1963) pointed out that scientific activity had been doubling essentially every fifteen years for some three centuries. Although this doubling has undoubtedly leveled off, as all exponential trends must eventually, the volume of articles and patents in the modern world absolutely mandates the use of statistical indicators to characterize these activities.

Specifically, the situation is the following. Every working day more than 5,000 scientific articles are published in reputable refereed scientific journals throughout the world; every working day 1,000 or more new patent documents are issued throughout the world; and every working day the Japanese science and technology giant Hitachi obtains five new U.S. patents. Clearly

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it is beyond the ability of any person or group to comprehend all of this new knowledge or its implications, or even to measure it, without the use of quantitative indicators.

The first and most basic tenet behind bibliometric analysis is activity measurement: that counts of patents and counts of articles provide valid indicators of R&D activity in the subject areas of those patents or articles, and at the institution from which they originate.

The second tenet is impact measurement: that the number of times those patents or articles are cited in subsequent patents or articles provides valid indicators of the impact or importance of the cited patents and articles.

Finally, the third tenet is linkage measurement: that the citations from articles to articles, from patents to patents, and from patents to articles provide indicators of intellectual linkages between the organizations that are producing the patents and articles, and knowledge linkage between their subject areas.

In the rest of this brief article we will discuss how these three notions of indicators of activity, of impact, and of linkage can be used to address policy questions at the national level, strategic questions at the institutional level, and tactical questions of interest to the research manager. We will draw most of the illustrations from our recent technology work in patent analysis, which is newer and perhaps less familiar than science literature analysis, and will try to point out that analogous work has also been done in the literature.

EVALUATION LEVELS

The relationship between the three major levels of indicators analysis, and conventional searching and information retrieval, are summarized quite succinctly in Figure 1. The main point of Figure 1 is the idea that *policy questions* deal with the analysis of very large numbers of articles and patents, often hundreds of thousands at a time, in characterizing the scientific and technological output of nations and regions. *Strategic analysis* tends to deal with thousands to tens of thousands of articles or patents at a time, numbers that characterize the publication or patent output of universities and companies. *Tactical analysis* tends to deal with hundreds to thousands of articles or patents, and deals typically with activity within a specific subject area. Finally, conventional information retrieval tends to deal with identifying individual articles, patents, inventors, and clusters of interest to an individual scientist or engineer or research manager working on a specific research project.

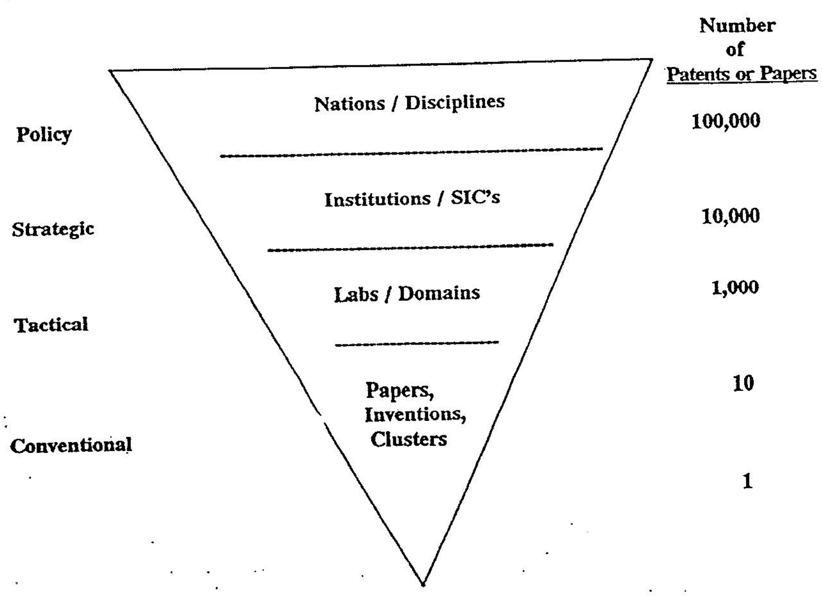

Figure 1: Evaluation Levels

POLICY APPLICATIONS

The first widely known policy document containing extensive bibliometric data was the National Science Board's *Science Indicators 1972* report, which contained basic information on the number of publications, and how frequently they were cited, for six major countries and seven scientific fields, to provide basic indicators of the major areas of activity of these major countries. Citation counts to the journals containing those articles provided basic indicators of the impact of the article on a country-by-field basis.

Subsequent biennial updates of that report series, through to the most recent *Science and Engineering Indicators 1992* have expanded the indicators to include data for more than 150 countries, to refine the classification to 100 subfields, to include international cooperation as measured by coauthorship, and to include measures of research linkage and cooperation as measured by citations from sector to sector of the U.S. scientific community. These basic findings have been widely reported in the press, and have led, in related work, to much controversy over whether the UK position is slipping in basic science (Martin et al. 1987). They also, in a much less controversial way, solidified the view of the Soviet Union as being very weak in many areas of science particularly related to modern biomedical and genetics research, the Japanese particularly strong in engineering and technology, the Germans strong in traditional chemistry, and the United States still the overall dominant country, with a particularly strong position in biomedicine.

The more recent science indicators reports, and other ongoing research, have expanded these techniques to technology indicators, and to comparing the positions of countries as measured by their patent output. Most of these patent studies use the U.S. patent system as their base, because the system has been fully computerized since 1975, because it is the largest patent system in the world, and because it is the system of choice for patenting by any company planning to market in the United States. Furthermore, because half of all U.S. patents are of foreign origin, and each country patents in the United States in proportion to its gross domestic product (GDP), the U.S. system is also the system of choice for international comparisons (Narin 1991).

One particularly high-impact application of policy-level data was the New York Times article "In the Realm of Technology, Japan Looms Ever Larger," with a map of the world showing each country's size proportional to its technological strength (Broad 1991). In that article technological strength was measured by the number of U.S. patents issued to companies in that country in CHI Research's TECH-LINE™ database, multiplied by a citation weighting, so that more highly cited patents have a higher weight (CHI Research 1992). That map shows that, by the late 1980s, Japan was larger in technological strength than all of Western Europe combined, Taiwan was almost as large as Canada by this measure, and both Taiwan and Canada were larger than the former Soviet Union. Even more remarkable, if the same map were prepared for just electrical and electronics patents, Japan would not only be larger than all Western Europe combined, but by 1989 Japan would be, by this measure, larger in electrical/electronic technological strength than the United States itself in the U.S. patent system.

Finally, in some very recent research, the citations to scientific articles from the front pages of U.S. patents have been analyzed to get a quantitative measure of the linkages between scientific and technological activity (Turney 1991, 40; Narin and Whitlow 1990). This analysis has led to Figure 2, which shows the percentage of citations from each country's patents to each country's articles divided by the percentage of published articles that are from that country. Thus the expected value of each of those columns is 1.0, and the rather high diagonals, averaging 3.0, show that each country's patents in the United States cite their own scientific articles three times as often as

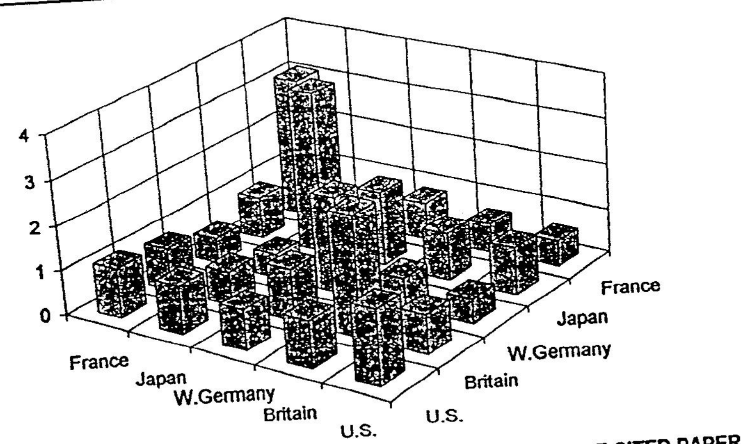

Figure 2: Linkage Between Technology and Science

would be expected, even after adjusting for the size of the country's science. This finding argues, quite eloquently, for the importance of domestic science to domestic technology, and certainly has vast implications in the science and technology policy arena.

POLICY-LEVEL LIMITATIONS

The major problems with bibliometrics at a policy level are those of data access and complexity, and of representativeness. Patents and articles are, after all, just reflections or representations of the underlying scientific activity—they are not the activity itself, and therefore, indicators built from patents and articles cannot be perfect. Furthermore, there are some areas of technology where trade secrets are more important than others, although in most of the major areas of chemistry, biomedicine, and electronics, patents are becoming very important, and more central, and clearly play a crucial role in the protection of company technology.

The problem of weighting, of distinguishing between important and unimportant patents and articles, is usually addressed through citation analysis. The basic weighting assumption, validated in many studies, is that if a sufficiently large number of patents or articles are being considered, then the patents or articles that are highly cited are of much greater impact than those articles or patents that are never cited, or only cited once or twice.

It is also critically important in valid bibliometrics to normalize the data, that is, to account for the differences between fields, subfields, and nations in their publication and patenting patterns. For example, a typical article in biochemistry contains twenty or more references, twice as many references as a typical article in acoustics, and those biochemistry references have a much shorter time span than the acoustics references. These two factors combine and result in much higher citation rates for biochemistry articles than for acoustics articles. It is therefore quite misleading to compare the citation rate of an acoustics article with that of a biochemistry article. Each patent or article should be compared, in a normalized manner, with the average for its own research area.

There are also major differences in the way citations are timed from one country to another. For example, as shown in Figure 3 for Germany, a country's articles tend to cite other articles from the same country much more rapidly than they cite articles from outside of the country. A lot of this, of course, is due to quick self-citation to a scientist's own earlier articles, and to the work of colleagues within his or her own institution, and the older cites to articles from other countries, which probably reflects the time it takes for published knowledge to diffuse throughout the research community. Nevertheless, any cross-national or institutional citation analysis that does not take this into account is certainly going to be biased, especially in short-time scale comparisons of U.S. and foreign institutions. Because there are more U.S. articles than there are articles from any other country, and because these are much more likely to cite articles from other U.S. institutions, this will severely bias any short-time frame analysis against non-U.S. institutions.

STRATEGIC APPLICATIONS

The strategic applications of bibliometric techniques tend to be those that deal with institutions, either universities or research laboratories in the literature area, or companies and their research laboratories in the patent area.

For example, most of the very early ranking and evaluation of universities was done in the Roose-Andersen and Cartter reports (Cartter 1966; Roose and Andersen 1970) entirely by peer review. Gradually this peer review has come to be supplemented by bibliometric techniques. In a bibliometric article by CHI Research, peer review rankings were shown to contain a significant amount of halo effect, but also to be generally in quite close accord with

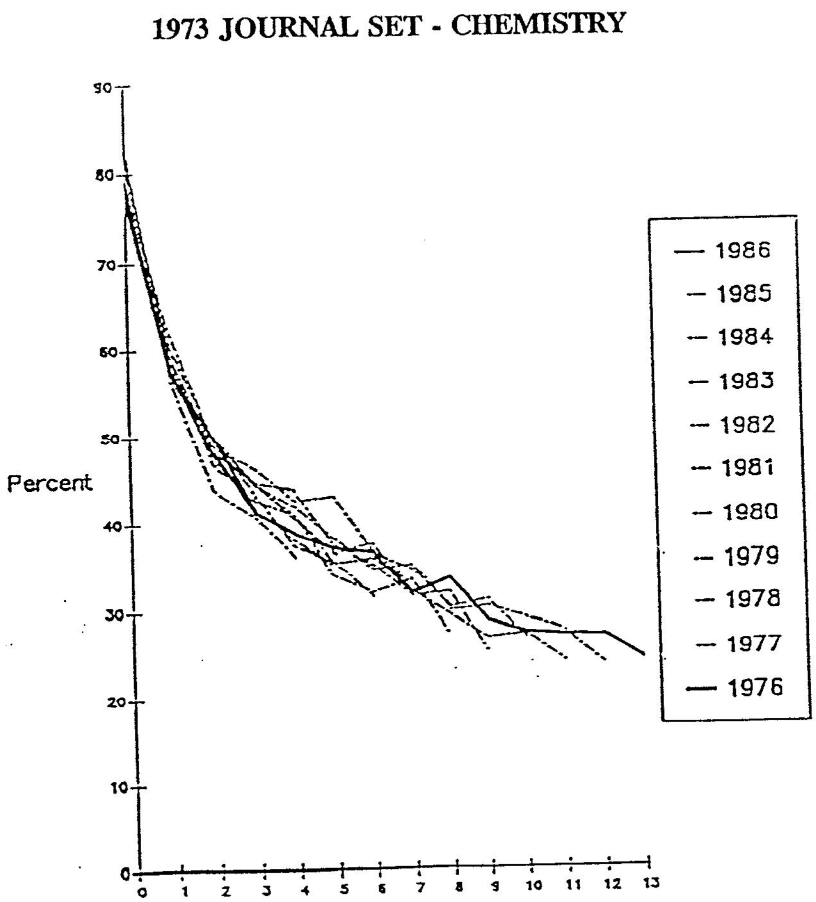

Figure 3: Percentage of West German Cites to West German Articles

bibliometric rankings (Anderson, Narin, and McAllister 1978). Furthermore, the bibliometric rankings of the institutions, when they included citations, tended to be in much closer agreement with peer opinion than rankings based just on publication counts. There have since been many bibliometric studies ranking institutions in many different fields of science, based on both publications and citations. Although these studies are controversial, the technique is steadily gaining acceptance and becoming more and more widely used.

In the patent area strategic analysis is at a much earlier stage. The only large-scale public application of strategic-level data was the recent *Business Week* patent scoreboard, which ranked more than 200 companies within thirteen different industries, based on their technological strength (Buderi et al. 1992). That article also contained an additional indicator of corporate technological performance, technology cycle time, defined as the median age of the references cited on the front page of the U.S. patents.

From a strategic viewpoint technology cycle time turns out to be quite an interesting indicator, and generally reveals a sharp international progression. The shortest technology cycle times, in this sense, are obtained by Japanese companies, with U.S. companies typically one year or so slower than the Japanese companies, and European companies one year or so slower than the U.S. companies. There is also one relatively large-scale, on-line database, CHI's TECH-LINE™, on Mead Data Central's NEXIS/LEXIS service, which contains technological profiles of more than 1,000 companies based on patent citation analysis. TECH-LINE™ is just beginning to be used in financial and competitor evaluations.

STRATEGIC-LEVEL LIMITATIONS

At the strategic level there are many complex aspects that have to be taken into account to do valid, useful bibliometrics. To start, in almost all cases the origins of the articles and patents are not identified in a fully unified way. There are hundreds of variants of the name Harvard University in the *Science Citation Index*, and there are more than fifty different names under which the German company Bayer currently patents in the United States. All of these must be unified to identify data at an institutional level. There are also the problems of accurately matching citations to articles, with the many inaccuracies that occur in that process.

There is an additional problem in data normalization. It is very difficult to do proper data normalizations from on-line or compact disc-read only memory (CD-ROM) versions of the scientific or patent databases.

In the patent area one major problem is that analytically usable, machine-readable data for European patents is not yet available. As a result, there has yet to be any large-scale research on the citation properties of European patents.

Finally, for strategic work there is always the problem of classification—there is no perfect classification system, and in any precise evaluation a specially tailored classification system, either for articles or patents, seems to be mandatory. The classification systems that are normally associated with articles such as the medical subject headings (MeSH) from the medical literature analysis and retrieval systems (MEDLARS), or the patent classes and subclasses used by the U.S. or international patent offices, all tend to be designed for retrieval purposes, and therefore are highly redundant. This redundancy, although of great use in retrieval, tends to introduce articles and patents that lie outside the bounds of a strategic analysis, so that selecting and classifying articles and patents is always a major challenge in this type of research.

TACTICAL APPLICATIONS

By tactical applications of these techniques we mean analyses that are directly applicable to the conduct or management of research and development. The line between a tactical application of bibliometrics and a conventional literature or patent search, which should be undertaken before any research project is begun, is relatively fuzzy. The main differentiation is the viewpoint: a tactical analysis attempts to model what is going on in a research area, to look at its development, progress, and future direction from a somewhat broader viewpoint than a conventional analysis.

One example of this that encompasses both science and technology is CHI Research's "Three-Plane Model of Technological Development." In this model the technological activity being directly analyzed takes place in the central or technology plane. However, the technology plane is based on and built from a precursor or base plane containing the articles and patents cited by the patents in the technology plane, and is followed up by the patents in the successor plane, patents that are citing to the patents in the technology plane.

A specific example is in a recently published article on memory-enhancing agents (MEA), and shows that the MEA technology plane is quite heavily dominated by one company, Hoechst-Roussel, which has a set of highly interlinked patents related to the enhancing of human memory in that plane (Narin, Smith, and Albert 1993). Specifically, the technology plane is a set of patents that are very specifically related to the enhancing of human memory.

Figure 4 is a diagrammatic representation of all three MEA planes, and shows, in the central or technology plane, the dominance of Hoechst-Roussel as a main player. Of particular note is the base plane, which consists both of cited patents and cited articles, and contains more articles than patents. In

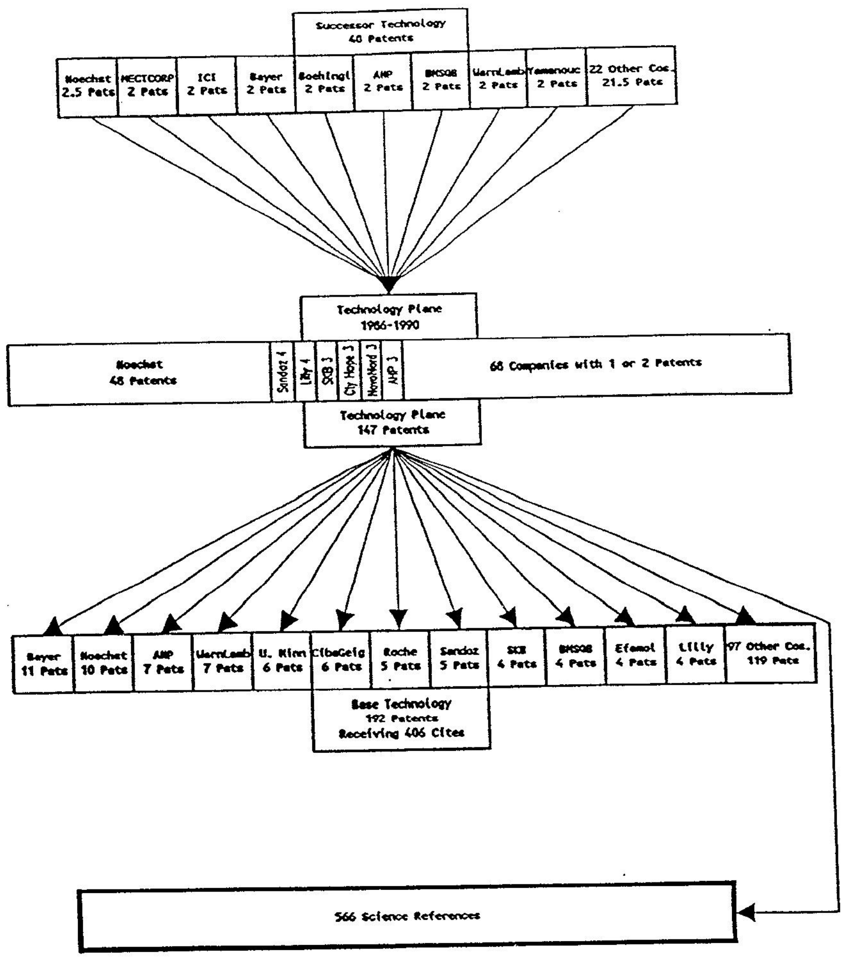

Figure 4: Three-Plane Model

this technology, on the front pages of the U.S. patents, there are more references to nonpatent materials, the great majority of which are scientific articles and books, than there are to patents themselves. This is characteristic of many advanced areas of biotechnology. The base of this technology lies as much within science as it does within technology.

The successor plane, shown at the top of Figure 4, is the set of patents that cite to the patents in the technology plane. These are generally in other areas of biotechnology, not memory enhancing per se, but related areas, such as cognitive stimulation.

The key point of this example is the more or less formalized representation of the development of technology, from its precursor science and technology, to the technology itself, onto successor technology opportunities. We have found this systematic way of tracing the development of research to be quite useful in evaluating progress in a research and development area, and in trying to ascertain whether a company is central or peripheral to that progress.

FINAL OBSERVATIONS

In this article we have shown how bibliometric techniques, both for patents and articles, can be used to evaluate technical activity at three different and quite distinct levels: at the policy level, where the performance of nations or regions is being evaluated; at the strategic level, where the performance of companies or universities or departments might be under analysis; and at the tactical level, where one is trying to identify and evaluate important aspects of a particular technological development.

In all these cases, and at all these levels, the fundamental process is the same; assemble the data, define the indicators, characterize the players, evaluate the key activity, and from that reach a data-based evaluation. Although there are operative difficulties with definition, difficulties with unification, and difficulties with classification at every level of the analysis, the objectivity of this kind of evaluation technique provides a very important adjunct of supporting data and quantitative guidance to the ultimate decision of an evaluator.

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