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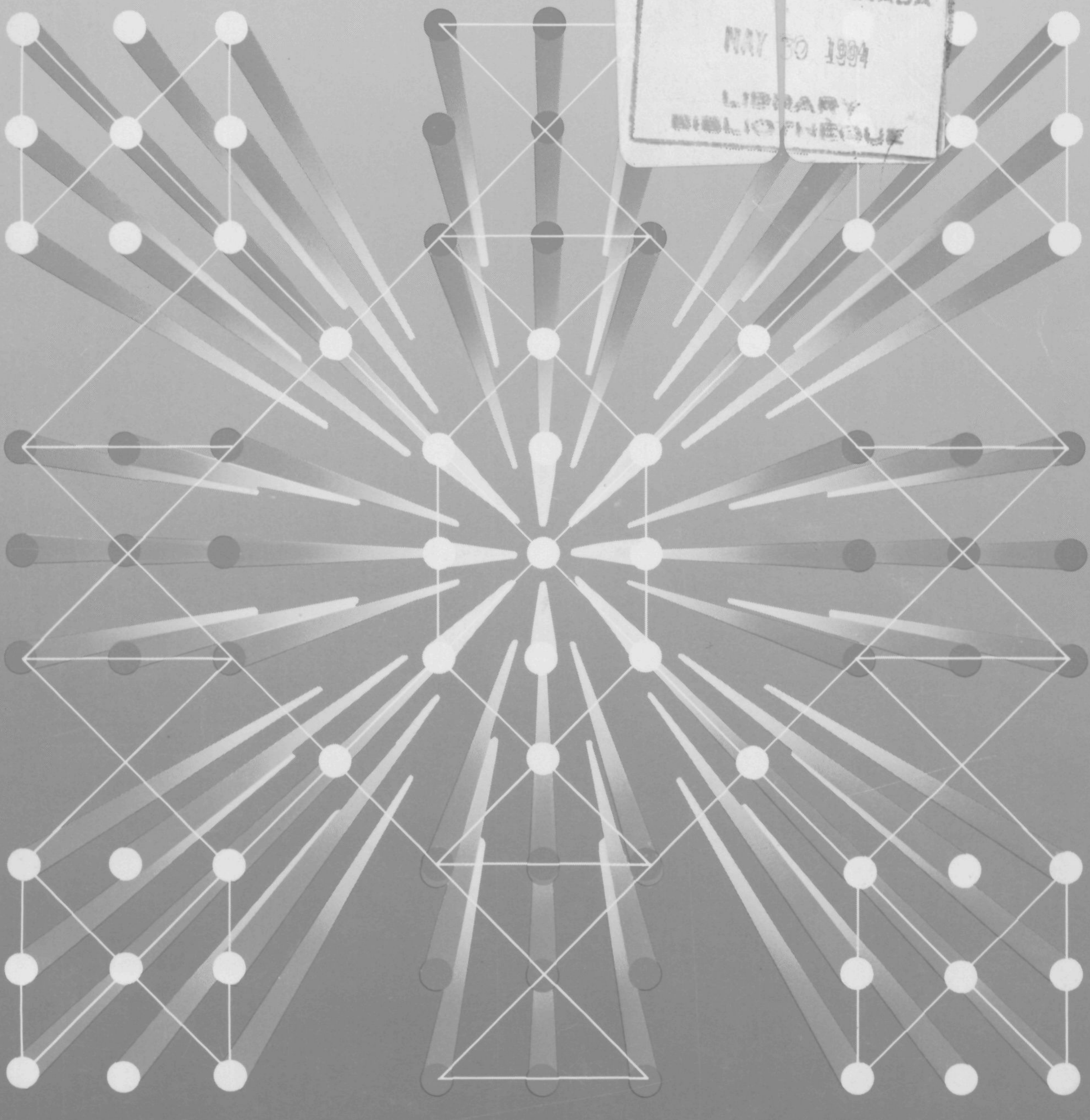
An Indicator of Excellence in Canadian Science: Summary Report

by James B. MacAulay



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An Indicator of Excellence in Canadian Science: Summary Report

by James B. MacAulay

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PREFACE

This paper describes the theory of bibliometric analysis, outlines the limitations of a citation index to papers and journals, and presents selected results of a pilot project in bibliometrics involving an evaluation of the research papers and journals monitored by the Institute for Scientific Information. A more complete examination of the above topics is contained in a report entitled **An Indicator of Excellence in Canadian Science** which should become available in late 1984.

Science and technology indicators may be defined as statistics which measure quantifiable aspects of the creation, dissemination and application of science and technology. As indicators, they should help to describe the science and technology system, enabling better understanding of its structure, of the impact of policies and programs on it, and the impact of science and technology on society and the economy.

An Indicator of Excellence in Canadian Science: Summary Report is one of a series of background papers on science and technology indicators to be published by Statistics Canada. The purpose of the series is to describe the theoretical development, limitations and application of various statistics suggested as indicators of science and technology.

Current indicators of Canada's scientific and technological activities include:

- expenditures on research and development;
- federal government scientific activities;
- personnel working in science and technology;
- Canadian research output (citations);
- Canadian patented inventions;
- international payments and receipts for technology;
- trade in selected commodities.

Statistical tabulations of the indicators will be released in **Science and Technology Indicators,** Catalogue 88-201, an annual summary; **Industrial Research and Development Statistics,** Catalogue 88-202 (annual); **Resources for Research and Development in Canada,** Catalogue 88-203 (annual); **Federal Science Activities,** Catalogue 88-204 (annual); and in a monthly service bulletin, **Science Statistics,** Catalogue 88-001.

A list of the proposed background papers is included at the end of this publication. These papers represent the opinions of the authors and do not necessarily represent those of Statistics Canada. Comments are invited and should be addressed to Karen Walker of the Science and Technology Statistics Division.

This summary report and the main paper have been prepared by James MacAulay of the Information Analysis Group (17 MacLaren Street, Ottawa, K2P 0K3). Charles Colbourn and Marlene Colbourn (University of Saskatchewan), collaborated in the development of a computer algorithm for the implementation of the pilot project.

Martin B. Wilk
Chief Statistician of Canada

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INTRODUCTION

The exchange, evaluation and public recognition of scientific research are essential to the development of science. Scientific literature functions as a communication system whereby new knowledge may be submitted to the science community to acquire its value as a public good.

The formalization of the process of scientific correspondence was one of the important achievements of the scientific societies of the seventeenth century. Formal accounts of discoveries were circulated as journal papers or letters, and these became the chief instrument for making priority claims in intellectual property (i.e., knowledge) and for having those claims evaluated by peers. More effective means have since evolved for communication in science, but the research journal has survived and prevails today because it is fundamentally a means for making knowledge claims rather than merely assisting in a flow of information. More precisely, it permits individuals or groups to place their intellectual property in the public domain in exchange for recognition by their peers for their priority of discovery.

Many aspects of science can be investigated by examining the system of documentation. Such study is known as bibliometrics. The field of bibliometrics concerns itself with developing measures of the characteristics and properties of a system of documentation in order to exhibit some feature of the knowledge and the knowledge community represented therein. Because of the subject matter and the theoretical requirements for its analysis, bibliometrics has become a branch of information science, benefiting greatly from the related areas of information retrieval systems and mathematical linguistics. Nevertheless, many of the techniques commonly used in bibliometrics have been developed in an uncritical way (publication and citation counting are familiar examples), the results of which reflect the character of the available data base rather than the character of science.

This report discusses the theoretical aspects of bibliometrics and describes various types of science indicators. It also presents selected results of a pilot project involving an evaluation of research papers and journals. (These topics are developed in greater detail in the main report.)

Chapter 1

BIBLIOMETRIC ANALYSIS

Definition, Purpose and Limitations

Scientific knowledge must be communicated in written form and circulated among peers in a research community to be acknowledged. Typically this takes the form of an account of selected research findings published as a document in a journal. The purpose of a bibliometric analysis is to derive measurable variables from a system of documentation that are characteristic of the scientific knowledge represented therein, and of the research community in which it is to be circulated. The purpose of the analysis summarized here is to derive a family of indicators that are descriptive of trends in the direction and levels of activity within science, and evaluative with respect to the quality and relevance of that output; and more specifically, to derive indicators of excellence in Canadian science.

Such bibliometric indicators provide useful information for the consideration of science policy issues at both national and organizational levels, and for testing hypotheses which arise from the social studies of science. Applications of the latter type stress an analysis of the structure and dynamics of research areas. We are concerned here with policy-relevant indicators which have a different emphasis -- the identification of output trends and the quality of papers at national, sectoral and organizational levels.

Possible sources of error in an undertaking of this kind can be divided into three types.

(1) Errors derived from failing to take into account intrinsic characteristics of science and scientific literature. Examples of this type of error would arise if one did not acknowledge the radical variations in the production, citation behavior and rate of self-citation among disciplines as well as variations in authorship characteristics.

(2) Errors derived from the character of the information source or data base. These include geographical, linguistic and disciplinary bias in the available sources of bibliometric data as well as some variation in editorial policy, on a national and disciplinary basis with respect to rejection rates and lengths of articles.

(3) Errors introduced by inherent limitations of particular methodologies. This source of error arises from the use of subjectively derived and grossly aggregated classes of journals. Classes that are too heterogeneous and ill-defined do not allow the development of measures that might otherwise overcome the two other types of errors.

Perhaps the most important point in developing a technique which overcomes these types of errors is to avoid making the assumption that a flow of knowledge or information can be measured directly. The choices involved in authoring, co-authoring, vocabulary and citations indicate a complex and formalized process. Thus, the documentation of science represents research as a dynamic process of inquiry and learning. In this context, we cannot measure information as a flow, but we can discern certain important and measurable characteristics of information sources which result from the process of inquiry. Research documentation is a rich source of quantifiable information. Each paper (identifiable by journal, volume, issue, page and year) contains the author's name, country of residence, institutional or departmental address, key words in title, abstract and full text and references to cited documents. These data within an information source can be sorted and analysed to yield many descriptive and analytical type indicators. It will be useful here to describe briefly the different types of indicators.

Types of Literature-based Indicators

The first distinction to be made is between indicators which are purely descriptive of research activities, and those that are analytical with respect to those activities. An example of the former would be a time series of the Canadian share of papers in a group of journals representing a certain research area. An example of an analytical indicator would be one which evaluated the relative importance of those papers, perhaps finding that given a certain share of papers in an area, the Canadian contribution was disproportionately influential.

It is also useful to introduce a second dimension, distinguishing the range of the indicator. Firstly, at a micro-level, indicators might be developed with respect to individual investigators, research groups, or laboratories. Secondly, one might define indicators with respect to research areas, i.e., middle-range. Finally, national or international comparisons would be the most general or macro-level of indicator. Thus we can consider six classes of indicators. Within each of these, valid and useful indicators can be developed. A brief outline of each class follows.

(1) Descriptive Micro-level Indicators

This indicator class refers to data on the frequency of publication or of citation to authors or laboratory addresses. It is easy to assemble such data since reference departments of most science libraries have publications and citation indexing services such as the **Science Citation Index** and **Who Is Publishing In Science,** both produced by the Institute for Scientific Information (ISI).

(2) Analytical Micro-level Indicators

Indicators in this class are derived from an evaluative analysis of papers or of journals based on some measure of their impact. They are in turn often coupled with other results derived from an organizational analysis. These indicators will typically try to select 'high quality' papers and provide profiles of organizational activity and its impact, possibly comparing an organization's share of all papers in a research class with its share of the strongest papers.

(3) Descriptive Indicators in the Middle-range

As noted earlier, many of the most fundamental bibliometric characteristics change from one research area to another, therefore, it is important to be able to draw reasonably accurate boundaries around research classes of journals and papers. Any descriptive indicator based on research fields must involve at least some pre-analysis of journals into classes which are roughly comparable and in the same field. Such indicators as time series of the output or impact of papers can then be controlled in a meaningful way. Indicators that have been developed with respect to some form of control over research areas could be considered to be middle-range indicators.

(4) Analytical Indicators in the Middle-range

This class refers to indicators derived from further analysis of the impact or relevance of the system of papers and then aggregated by the different research areas. Analysis here refers to some method for evaluating papers, and clustering them into research specialties. The immediate indicators obtained from an analysis of literature into research classes have more direct relevance to the sociology of science. However, by attaching individual and national addresses, a whole range of indicators can be developed. The results are profiles and measures of dispersion of important papers among countries, organizational locations and authors.

(5) Descriptive Macro-level Indicators

Assuming that some acceptable form of pre-analysis grouping of journals into fields has been carried out, this class of indicators simply attaches national addresses to papers and generates indicators which describe, in time series for example, the changing national shares of output, and some impact indicators such as the citations generated per publication. Multiple-authored papers are normally allocated among addresses.

Marginal changes in the national shares of papers and citations can be meaningful and useful within carefully controlled clusters of journals. Another group of useful descriptive indicators along these lines results from allocating organizational addresses to sectors. Then the collaboration, for example of university and industry units through co-authorships, can be examined.

(6) Analytical Macro-level Indicators

One shortcoming of the above indicators is that they do not evaluate the quality of papers, but use instead the proxy of the impact of journals. For this last type of indicator, papers are analysed for their relevance in the whole system, and then allocated to journal classes and within each journal class, ranked from most relevant to least relevant.

By attaching organizational and national addresses to these papers, their relevance can suit a variety of purposes. One of these is to compare the share that a location or country has of all relevant papers to its share of the upper decile and percentile of most relevant papers. It is also interesting, for papers in the top percentile, to identify their authorship. These results can be correlated with other forms of peer evaluation such as ratings of graduate schools and levels of funding by peer evaluation panels. Organizational and national profiles of the distribution of relevance shares among specific journal classes are also useful and more informative than similar profiles constructed from publication or citation shares.

Having outlined the range of bibliometric indicators that can be developed, we now turn our attention to the strategy used in the pilot project to derive the relevance of papers of the information source. We begin by describing the term "relevance".

Computing Relevance Among Cited Papers

From previous discussions it can be concluded that the process of inquiry and learning is both intellectually costly and time dependent. What the user of an information source may find valuable is very much dependent upon his current state of understanding and hence where, at a given moment, that user has been obtaining useful information. Accordingly, inquiring users trace out quite specific directional pathways among the elements of an information source such as the ISI Citation Index.

A formalized inquiry process such as may be represented by authors citing a selection of research papers, is constrained by these personal, as well as disciplinary, factors. The notion of the conditional relevance of a paper to an inquiring user introduces the idea of the analysis of an information source based on a matrix of transition probabilities of users referring among source papers. In turn, this leads to the concept of "relevance" among papers.

Mathematically, the transition probability measures the likelihood/conditional probability that, given that an author makes reference to a certain paper which is in the citation index, he will make reference to another specific paper in the index. That is to say, it represents the likelihood that, given a paper in the citation index was useful to an inquirer, the paper directed him to another paper in the index which was also of use. This means the two papers are associated together in terms of intellectual distance (i.e., a relation of influence exists between the two papers), and a direction has been attached between papers (i.e., one inquired from one paper to another). While the transition probability reflects the relation of influence between papers, it suppresses the relative importance of the various linkages. This factor is re-introduced by measuring the contribution of each linkage (i.e., pair of papers) to all possible linkages from the citation index.

Therefore, we derive two probability measures, (1) the propensity of authors to refer from one paper to another (transition probability) and (2) the relative frequency with which each of these ordered pairs is chosen from among all ordered pairs of papers. These two measures are the basis of the term we call "relevance".

The relevance measure defines a set of mathematical relations among papers, the properties of which permit us to order those elements into chains and to partition them into exclusive classes. These properties permit us to obtain the relevance of any cited paper to all other cited papers (the sum of the relevance of each of the linkages to a paper from all other papers), and the relevance of any class of cited papers (the sum of the relevance of all papers in terms of a specified research area).

To summarize, relevance relations reflect a collective evaluation of influence among papers in a scientific field. Perfunctory, prestige and self-citing behaviors notwithstanding, the citation indicates an acknowledgement of knowledge claims. However, because of such variations in citing behavior and because of the biases which result from the error types noted earlier, the citation cannot be quantified as a measure of information flow. Rather, it can be used to derive two probability measures which are not sensitive to these sources of error and, no amount of self, prestige or perfunctory citing, nor bias in monitoring the source, will alter the relations of influence which are thus collectively imposed by the research community itself.

The method of analysis and evaluation outlined above was implemented in a large scale pilot project for the Science Council of Canada using the journals monitored by the Institute for Scientific Information (ISI). ISI monitors 4,000 journals; this involves preparing a list of all references made in each paper in each of the journals. This reference list is sorted to obtain an index of citations. In the pilot project the 1978 citations were analysed for all papers published in 1974 to 1976 in the ISI monitored journals. A computer algorithm was devised and used to: (1) evaluate the relevance on all ordered pairs of the 4,000 journals; (2) evaluate the relevance on all ordered pairs of papers published in those journals in the three selected years; and (3) analyse the structure of the journal system by entering relevant linkages incrementally (i.e., in terms of marginal relevance), thereby ordering the citation index into chains of connected elements, and finding classes of interconnected elements. The latter part of the procedure involves a graph theoretic algorithm devised by Charles and Marlene Colbourn of the University of Saskatchewan, details of which can be found in the main report. Thus, the whole system of journals was subjected to an objective analysis and classification, while the papers published therein underwent a systematic evaluation.

Chapter 2

SELECTED RESULTS

The pilot project carried out at the Science Council of Canada was unique in several respects, but chiefly in the fact that it managed to avoid the arbitrary classification of input data. It also ranged over the entire system of scientific documentation and as one might expect, produced a large quantity of results. We summarize them here on a selective basis, indicators related to science policy, favouring mainstream rather than peripheral areas of research, and singling out indicators of Canadian participation in this context. For additional detail, the reader is referred again to the main report.

Our summary proceeds along the following path: first there is a brief discussion of the structural analysis of the journal system employed and resultant descriptive indicators followed by a summary of indicators based on the evaluation of papers.

A Structural Analysis of the Journal System

While there is no practical limit on the numbers of papers or journals that might be evaluated, an efficient clustering algorithm for more than 20,000 papers will exceed the capacity of present generation computers. This means that while relevance in the entire system of papers can be evaluated, a classification procedure, if it is to be handled objectively, must be based upon a preliminary structural analysis of the system of journals.

As noted, the ISI monitors over 4,000 journals, including the social sciences. In terms of journal-to-journal citations, these turned out to be rather strongly interconnected: about 4.6 million ordered pairs had non-zero relevance, out of a matrix of 16 million possible linkages. The top journals in order of their relevance in the system generally coincide with one's subjective notions of important journals: (1) **Nature,** (2) **Science,** (3) **Journal of Biological Chemistry,** (4) **Proceedings of the National Academy of Science,** (5) **Biochimica et Biophysica Acta,** (6) **Lancet,** (7) **New England Journal of Medicine,** (8) **Journal of Clinical Investigation,** (9) **Annals of the New York Academy of Science,** and (10) **Journal of the American Chemical Society.** Other familiar mainstream journals include **Physical Review Letters,** which was Number 29, and **Royal Society of London, Proceedings, Series A,** which was Number 38. The top Canadian journal was Number 54, **Canadian Journal of Chemistry.** It is well known that Canadian researchers tend to publish heavily in American, British and major international journals, and their work is cited more frequently when they do this. The result, however, is that aside from the Canadian journals of chemistry and of biochemistry, we have very few journals with real international strength.

Although, the evaluation of journals was incidental to our main purpose of doing a relevance evaluation at the refined level of cited papers, an initial journal analysis was necessary in this scheme in order to classify relevant papers. Using the graph theoretic algorithm we obtained a clustering of some 85 classes of those journals with at least a minimal degree of relevance in the system. Of course, many of these classes are somewhat peripheral, and as one would expect from the literature of information science, a distribution of relevance among journals is highly skewed. As noted, the algorithm works incrementally from the most relevant to the least relevant. By the time it has consumed about 1% of the 4.6 million relevant inter-journal linkages, it has accounted for over half of the relevance in the system.

The 85 classes of relevant journals contain only 1,468 minimally relevant journals, out of the 4,000 journals considered initially. In a subsequent iteration, the algorithm found 36 classes of disciplinary fields. The strongest class is a multidisciplinary cluster of main biochemistry journals which incidentally contains a clique (i.e., maximally joined subset) of the five strongest journals in the whole system.

The influence of these few journals extends throughout the system and together with the classes of main chemistry, main medicine, physics and applied chemistry, they largely define the central core of an outwardly spiralling system of influence. In other words, the structure of the literature system is more complex than a simple lattice of basic and applied research classes, as historians have traditionally presented it.

Appendix I lists the journals in three of these classes in order of their influence in the system. Each listing also contains some information on when the journals were founded, their location and language of publication. A complete listing and a structural description may be found in the main report.

Descriptive Indicators Based on Journal Classes

By controlling the journal classes over time, useful series of descriptive bibliometric indicators may be collected and made meaningful. For example, despite the biases in international coverage, one can reasonably observe trends in national and organizational shares of publication within research areas, and if no more refined evaluation of papers is at hand, these can be weighted by the relevance of journals. Table 1 shows a sample of this type of indicator for the mainstream classes of chemistry, biochemistry and medicine. This type of data is really a by-product of work on more refined and evaluative indicators which are described below. Over the whole journal system, the levels of publication activity appear to reflect changes in the available levels of funding in the seventies. This generalization would not hold, however, for the quality of the output.

TABLE 1. Changes in World Shares of Papers in Three Journal Classes, 1974 and 1978

Country	1974	1978
	per cent	
Main Chemistry		
U.S.A.	46.9	43.3
Japan	11.0	11.9
West Germany	8.0	11.0
Canada	7.4	6.9
France	4.8	5.3
Switzerland	2.5	2.3
England	5.2	4.8
Italy	2.5	2.6
Israel	1.4	1.0
Netherlands	1.3	1.4
Main Biochemistry		
U.S.A.	57.0	55.5
England	9.8	8.6
West Germany	3.9	4.4
France	4.0	4.5
Japan	3.4	4.3
Canada	3.6	3.1
Sweden	2.0	1.8
Netherlands	1.4	2.1
Israel	1.7	1.7
Italy	1.7	1.7
Switzerland	1.2	1.6
Australia	1.6	1.5
Scotland	1.2	1.0
Belgium	0.8	1.1
Main Medicine		
U.S.A.	64.8	62.6
England	14.6	15.0
Canada	3.0	3.1
Scotland	2.4	2.2
Japan	1.2	1.6
France	1.4	1.8
Sweden	1.4	1.6
Australia	1.3	1.1
West Germany	0.9	1.0

Between 1974 and 1978 the Canadian volume of papers in the main chemistry journal classification dropped by 3% from 1,116 to 1,083. This, together with the fact that total papers in these journals was increasing, resulted in a change of our world share of output in that class from 7.4% to 6.9% (see Table 1). In the same period, West Germany increased its share from 8.0% to 11.0%. Taking the 32 most influential journal classes, the overall level of Canadian output increased by 5% or more in only 14 classes. This pattern was repeated in the United States and England, but France increased by 5% or more in 22 classes, West Germany in 24, Italy in 27 and Japan in 28 classes. Such changes in world share may often signal something notable. For example, while West Germany was modestly increasing its share of mainstream chemistry, those papers were also disproportionately influential in the whole system (see Table 5).

Several additional types of indicator can be developed from these simple distributions of publications and citations within controlled journal classes. For example, the distribution of papers among countries demonstrates a shifting centre-periphery status in some established research areas. In general, the output of papers became more dispersed among countries in all major international fields, with the exception of the main biomedical classes (see Main Report).

Co-authorships among countries and among organizations within a country represent another useful type of output-based indicator. In 1978, for the main class of biochemistry, 65% of our foreign co-authorships were with the United States and 11% with England; Canada co-authored with 19 countries in all. In comparison the United States co-authored with 42. Nevertheless, this represents an increase in Canada's level of cosmopolitanism since 1974, when we co-authored with only 13 countries. In 1974 for all fields, 65% of our foreign co-authorships were with the United States, as compared with 60% in 1978. Over the 1974-1978 period we increased (on a much smaller degree) our linkage with several countries, namely England, France, Australia, Japan, Sweden, Italy and Israel.

Looking more closely at the Canadian scene, the same output data are quite informative with respect to organizations, and also, when aggregated, to the activities of major sectors of the research community. The concentration of Canadian activity in terms of publication remains in the universities with a strong concentration in the Federal Government as well (see Table 2). A rough comparison with the distribution of activity in the United States can be made, based on papers monitored for the Science Citation Index at ISI. The location dictionary used by Computer Horizons Inc. placed about 68% of publications for 1979 in the university sector (including medical schools), results similar to Canadian activities. However, U.S.A. industrial laboratories accounted for about 9% of their country's activity, while only about 2% of Canadian activity originated in the industrial sector.

TABLE 2. Distribution of Canadian Activity Among Sectors in 1974 and 1978

Year	Sector	Papers		Units	Logi
		number	%	number	
1978	University	12,760	69.7	47	- .3318
	Federal Government	2,337	12.8	22	- .3842
	Hospitals, including university clinics	2,327	12.7	173	+ .3923
	Business	404	2.2	172	- .2497
	Provincial governments	249	1.4	47	+ .2896
	Non-profit organizations	225	1.2	36	+ .3528
1974	University	11,394	71.7	48	+ .3344
	Federal Government	2,263	13.6	27	+ .4109
	Hospitals, including university clinics	1,571	9.9	146	+ .3724
	Business	354	2.2	142	+ .2673
	Provincial governments	202	1.3	50	+ .2727
	Non-profit organizations	214	1.3	32	+ .3483

Logi: This is a measure of the concentration of publication frequencies among locations. It varies on a scale from 0 to .5 such that if all papers tend to come from very few locations, the measure approaches its maximum.

Table 2 also includes some information on trends in the dispersion of efforts within these sectors. The dispersion of publishing among university and business units, many of which may be ineffectively small, has long been recognized as a problem for research policy in Canada. Normalizing these distributions, we can compare the degree of concentration, which is maximal at .5 for this measure. As expected, the degree of dispersion is great in both sectors, and furthermore, the dispersion of research activities would appear to be on the increase. This is so in the federal sector as well, although here the organizational units are too aggregated to be particularly meaningful. This pattern of increasing dispersion of activity is generally repeated on the world scene for those journal classes representing very established research areas, whereas the highly dynamic research of recent vintage, appears to be concentrated in a few laboratories in a few countries (see below).

Several policy initiatives in recent years have addressed the problem of inter-sectoral linkages. The co-authorship data again show the central importance of the university sector as the base from which collaborative interaction tends to be built up. But by far most interation takes place within the university sector and its surrounding health science complex. In addition to that, a few federal laboratories, such as those at Atomic Energy of Canada Ltd. (AECL), have been highly collaborative with the university sector, perhaps indicating the importance of some of their research facilities to university research.

Universities were responsible for even more linkages in 1978 than in 1974, but the situation for the business sector has remained isolated and unchanged. This is disappointing since closer links between the business and university sectors have been sought for some time. An examination of co-authorship matrices for particular journal classes in applied science indicates some development of linkages in information and computing, but the numbers are very small. The same is also true for food chemistry, pharmacy, micro-biology and polymer chemistry. These numbers would seem to indicate the movement and collaboration of isolated individuals, but this type of linkage has obviously not yet been successfully institutionalized. Rather than investigating the output profiles of the particular laboratories involved, we shall turn now to a brief discussion of the evaluation of papers and resultant quality of output.

Evaluation of Papers

For an evaluation of papers, the 1978 citations were examined for all papers published and monitored in the years 1974, 1975 and 1976. These years were chosen on the basis of a study of most cited years for each journal class, constrained by the fact that considerable expense is involved in the examination of the addresses for additional cited years. The more dynamic research areas have a comparatively recent vintage, in the sense that, for example, in main biochemistry in 1978 the maximally cited year was 1976. For most fields, at least half of all 1978 references were to papers published in 1974 or later, and the three years selected always included the maximally cited year. Following the procedure outlined above, we computed the relevance of each cited paper to all other papers in the 1974-1976 system, then used the journal classification to group relevant papers. For each class, we constructed a distribution of papers from most relevant to least relevant, so that one could identify national and locational shares of all papers as well as their shares of relevance in the most highly relevant papers in the distribution.

For example, Canada had 3.2% of all relevant papers in the main biochemistry class of journals from 1974 to 1976 (see Table 3). (It was shown on Table 1 that we had 3.6% of all papers in the class in 1974 and 3.1% in 1978.) However, our share of total relevance in the class was 2.9% and in the rank-ordered distribution, our share of the top decile was 2.7%, (and only 2.1% of the top percentile). Recall that relevance is a property of cited papers: an evaluation by the whole research community of the importance of each cited paper in relation to all cited papers. Given a certain share of the relevance of all papers in a class, then a competitive and healthy research community ought to maintain or increase in its share of relevance in the select inner circles of most relevant papers. From a distribution of the relevant papers in the main biochemistry class, one could conclude that overall, Canadian papers were slightly less influential than those from other countries, and also we had less than our expected share of the top papers. We shall note some individual exceptions to this overall picture, but in general, Canadian strength in biochemistry tended to appear in the more specialized and less influential classes of journals.

TABLE 3. International Research Performance in Main Biochemistry, 1978 Reference Year

Country	Share of relevant papers	Share of relevance	Share of top decile relevance	Share of top percentile relevance
U.S.A.	56.1%	61.0%	64.9%	63.2%
England	9.4	9.7	9.6	12.1
West Germany	4.7	4.0	3.1	0.5
France	4.6	3.7	3.3	3.7
Japan	3.7	2.7	2.2	0.4
Canada	3.2	2.9	2.7	2.1
Sweden	2.0	2.8	3.0	5.0
Netherlands	1.8	1.4	0.8	0.7
Israel	1.8	1.9	1.9	2.6
Italy	1.6	0.7	0.3	0.2
Switzerland	1.5	1.9	2.1	2.6
Australia	1.4	1.1	1.0	0.2
Scotland	1.0	1.1	1.2	2.1
Belgium	1.0	0.6	0.4	0.2

The results for main biochemistry are shown on Table 3 for all countries with at least 1% of the total relevance in biochemistry. The actual percentage shares for any given country are as noted, subject to several factors in addition to the quality of research. But changes in those shares, moving through the distribution to the most relevant papers, represent a key indicator of the overall quality of a country's output in that class of journals. Thus, the particular strength of biochemistry in England and Scotland stands out, and the papers from Sweden are especially noteworthy. It must be noted that regardless of the overall relevance of a country's contribution, individual investigators may exert great influence. A Canadian paper from McGill University and the Research Institute of Montreal General Hospital placed 16th in main biochemistry and was influential among papers in subsidiary classes: "Depressant action of TRH, LH-RH and somatostatin on activity of central neurons," **Nature,** 255 (May 15, 1975), p. 233, by L.P. Renaud, J.B. Martin and P. Brazeau. The paper identified an important class of large molecules which communicate with receptors in the brain and affect behavior.

Papers from Sweden, France and Japan were disproportionately influential in the main medical class (Table 4), with the United States dominating through the entire distribution. There are, of course, many less important medical classes, some of them are more specialized, and in a few of these, the Canadian output was more impressive. But it can be seen in the main report that the most influential research in Canadian medicine is frequently concentrated in a small number of locations.

TABLE 4. International Research Performance in Main Medicine, 1978 Reference Year

Country	Share of relevant papers	Share of relevance	Share of top decile relevance	Share of top percentile relevance
U.S.A.	70.0%	70.0%	71.5%	70.8%
England	10.6	8.9	7.7	7.9
Canada	3.4	3.3	3.0	1.9
Scotland	1.9	1.3	1.0	1.9
Japan	1.7	2.0	2.2	2.4
France	1.5	2.0	2.0	2.5
Sweden	1.3	1.9	2.2	3.3
Australia	1.2	1.4	1.4	1.0
West Germany	1.2	1.3	1.3	0.7

The disappointing reception for West German papers in biochemistry and main medicine was reversed for the main class of chemistry journals (Table 5). With less than 9% of the relevant papers in this class, West German chemists were nevertheless responsible for more than a quarter of the relevance in the top percentile of the distribution. English papers also much exceeded their share of the upper sections of the distribution.

TABLE 5. International Research Performance in Main Chemistry, 1978 Reference Year

Country	Share of relevant papers	Share of relevance	Share of top decile relevance	Share of top percentile relevance
U.S.A.	53.2%	49.3%	45.8%	42.7%
Japan	9.7	6.9	6.3	8.9
West Germany	8.7	14.6	17.2	25.2
Canada	7.4	6.2	5.5	3.6
France	4.1	4.7	5.3	3.4
Switzerland	2.7	2.1	1.7	0.4
England	2.5	3.8	4.6	5.7
Italy	2.4	2.5	2.8	2.7
Israel	1.3	0.9	0.6	0.4
Netherlands	1.0	1.4	1.8	0.4

Though a few individual Canadian papers appear among the most relevant in most journal classes, the influence of Canadian papers generally fails to meet the expectations one would have, based on our overall share of these distributions of papers. An exception in the medical field is a subsidiary class of biochemistry with some 29 journals in pharmacology, neurochemistry and clinical research. Canada maintained a strong share of relevance throughout that distribution, with two papers among the 10 most relevant (from McGill and Queen's Universities) and with five among the 60 most relevant. Another class in which Canadian papers were, as a group, impressive in world terms was in a field of applied physics and electronics where we had over 7% share of top percentile relevance. Unfortunately, this is an area in which our level of activity was also declining in the period (from 6.6% in 1974 to 4.8% in 1978). Main mathematics, physics, computer science, chemical analysis and ecological studies were also areas of overall Canadian strength.

Performance of Canadian Laboratories

While the few Canadian papers of very excellent quality in each journal class could be identified, a more systematic indicator can be obtained by examining the performance of Canadian laboratories on the distributions of relevant papers (discussed in the previous section). In this case, the frequencies may often be small and therefore they are given directly rather than as a share. All address records on each paper are taken into account and the relevance is fractionally allocated where appropriate.

Table 6 shows the seven Canadian laboratories with papers in the top percentile of relevance in main biochemistry. Some 88 Canadian organizations had relevant papers in this class, and 32 of them had papers in the top decile of relevance. Of the seven shown here with papers in the top percentile, the University of Toronto was most prolific with 282 appearances overall on relevant papers in the top 12 journals of biochemistry, 40 of them in the top decile, and four in the top percentile. (The latter were co-authored, and actually refer to just two papers.) However, the single McGill paper mentioned earlier was Number 16 among all papers in the class, placing McGill first in the top percentile. The five AECL addresses in the top percentile appeared on a single very influential paper which ranked Number 140; the National Research Council (NRC) had both Number 189 and Number 339; Ontario Cancer Institute had Number 268 and the University of Guelph, Number 270. The two papers from the University of Toronto were ranked 275th and 300th in the distribution, and the University of Montreal also had a paper (No. 334) in the top percentile.

TABLE 6. Canadian Laboratories in the Top Percentile of Main Biochemistry, 1978 Reference Year

Canadian rank	Organization	Overall frequency	Frequency in top decile	Frequency in top percentile
1	McGill University	144	18	1
2	University of Toronto	282	40	4
3	National Research Council - Ottawa	82	12	2
4	Atomic Energy of Canada Ltd.	8	5	5
5	University of Montreal	71	9	1
6	Ontario Cancer Institute	16	6	1
7	University of Guelph	20	7	1

It bears repeating that even in journal classes in which the overall influence of Canadian papers may have been disappointing, individuals will frequently contribute very significant work which is submerged in an overall picture. Several government laboratories and specialized research institutes, particularly in areas of medicine and applied chemistry, frequently turn out to be more important than university addresses. While we do not often find isolated and small facilities, it is clear that the highest quality of output is not at all a simple function of size, level of output or level of funding.

In main chemistry, Canadian university faculties produced three of the top 30 papers, publishing none of them in a Canadian journal. The University of Manitoba had Number 12, Alberta (five authors) had Number 14, and Western Ontario, Number 27. The most influential paper published in the **Canadian Journal of Chemistry** (Number 59) also came from Western.

Four of the top 30 papers in pharmacology and clinical chemistry were by Canadian universities staff: Number 3 from McGill, Number 10 from Queen's, Number 22 from Toronto and Number 28 from Saskatchewan. Table 7 gives a picture of the overall performance of Canadian laboratories in the top relevance percentile in this class. In a related class of journals in analytical chemistry, pharmacology and toxicology, the Canada Centre for Inland Waters (Federal Department of Environment) had the top paper in the whole distribution: "Determination of tetra-alkyl lead compounds in the atmosphere," **Journal of Chromatographic Science,** 1976/14/162, by Y.K. Chau, P.T.S. Wong and H. Saitoh.

TABLE 7. Canadian Laboratories in the Top Percentile of Pharmacology and Clinical Chemistry, 1978 Reference Year

Canadian rank	Organization	Overall frequency	Frequency in top decile	Frequency in top percentile
1	McGill University	133	7	1
2	Queen's University	43	9	4
3	University of Saskatchewan	25	7	1
4	University of Toronto	159	23	2
5	Ontario Cancer Institute	7	1	1
6	University of Windsor	3	1	1

Significant work in a subsidiary class of biochemistry and cell biology related in part to birth control technology seems to have developed at Sherbrooke, Laval and Montreal. The major theoretical contribution from the Renaud group was discussed earlier with regards to main biochemistry. This journal group includes the **Canadian Journal of Biochemistry** and Series B of both the **Transactions** and

Proceedings of the Royal Society of London. D.V. Naik at Sherbrooke had the top paper in the distribution and Laval produced Number 11. Indeed, Canada had nine papers in the top percentile, each from a different location as can be seen on Table 8. The location code used in the main report standardized the variant names of all Canadian addresses and was made to correspond with Statistics Canada sectoral divisions. However, it is well known that such clinics as Laval Centre Hospital are essentially part of the University medical school.

TABLE 8. Canadian Laboratories in the Top Percentile of Biochemistry and Cell Biology, 1978 Reference Year

Canadian rank	Organization	Overall frequency	Frequency in top decile	Frequency in top percentile
1	University of Sherbrooke	16	4	1
2	University of Toronto	148	12	2
3	Carleton University	20	4	1
4	University of Western Ontario	32	4	2
5	Sick Children's Hospital	22	3	1
6	Laval University	24	10	1
7	Ontario Cancer Institute	2	1	1
8	Laval Centre Hospital	1	1	1
9	Simon Fraser University	13	1	1

In the main mathematics class, a paper from the University of British Columbia was Number 2, and this contribution alone gave Canada a disproportionate share of the top percentile of relevance.

The applied physics and electronics class showed particular Canadian strength, as noted in the previous section. We had 18 papers in the top percentile, 17 of them among the top 100 world papers. Some 29 organizations contributed papers in the top decile of relevance; six of them are business firms, three federal departments and the remainder are university laboratories. Table 9 shows the 12 organizations with papers in the top percentile. The University of Windsor had the strongest paper,

TABLE 9. Canadian Laboratories in the Top Percentile of Applied Physics and Electronics, 1978 Reference Year

Canadian rank	Organization	Overall frequency	Frequency in top decile	Frequency in top percentile
1	University of Toronto	121	19	4
2	National Research Council	136	14	4
3	University of Windsor	18	3	1
4	Atomic Energy of Canada Ltd.	57	9	2
5	University of Saskatchewan	7	3	2
6	Queen's University	29	5	1
7	Trent University	2	2	2
8	University of Western Ontario	38	8	5
9	McMaster University	101	14	2
10	University of Montreal	48	9	2
11	University of Manitoba	23	3	1
12	University of Ottawa	13	1	1

Number 22, followed by the NRC and Trent with Number 28, Western Ontario and McMaster with Number 31, and Montreal, Number 32. AECL produced Number 43 and Number 48, McMaster had Number 44 and the NRC had Number 45. What is most impressive about Canadian performance in this journal class is its depth at a number of different laboratories in all sectors. Sixty-seven locations produced relevant papers, and 29 were in the top decile of relevance. Many of the key papers involved university collaboration with federal laboratories, and this would seem to be a key to the growing importance of the industrial contribution in this area.

Chapter 3

CONCLUSION

Our society and economy have been characterized by a growing reliance upon knowledge in the place of other forms of capital. It follows that policies for the production and distribution of knowledge can become critical in all areas, but particularly in areas of science and technology. The research enterprise in Canada is small and institutionally underdeveloped in many of the most critical areas. But this fact only emphasizes the requirement in policy making for very precise information about research activities.

Many kinds of surveys and areas of study exist which can yield information about science and technology and, over the past few years efforts have been made to develop indicators which would satisfy the growing requirement for policy-relevant information. Some of the resulting indicators have become specific with respect to research activities, but few have addressed the central policy questions of selection and evaluation. Bibliometric indicators offer their greatest promise precisely in this area.

Evaluation of research activities has traditionally been in the hands of peer representatives from the research community. Technical visiting committees and the peer evaluation panels of the Natural Sciences and Engineering Research Council are examples of how academic research projects are selected for public funding and their facilities maintained. Many of our research institutions were planned or initiated by the Associate Committees of the National Research Council, composed of senior representatives from the research community.

Bibliometric indicators of the sort described in this paper do not present an alternative to the process of peer evaluation. In reality, a bibliometric analysis represents a more valid and continuing evaluation of research by all the active investigators in the community, rather than limiting the process to the private choices of senior elites in the community. Therefore, it would seem desirable to develop bibliometric indicators to assist the traditional institutions with research evaluation and policy.

Appendix I

JOURNAL CLASSES OF MAINSTREAM BIOCHEMISTRY, MEDICINE AND CHEMISTRY

This is a listing of journals in three influential research fronts: biochemistry, medicine and chemistry. The listing adopts the following notation sequence, R.F.i:j, where i = research field and j = research front. The first sorting/clustering of journals into similar research areas results in the identification of various **research fronts.** Each research front is resorted into **research fields.** Within each of these classes the journals are listed in order of their total relevance in the system of ISI journals. Each journal listing contains information on when the journal was founded, where it was published, its percentage share of the relevance of all journals in the corresponding front, and the language of publication. Thus, reading under R.F.1:1, we find the journal "NATURE", founded in 1869, published in London supplying 14.4% of the total relevance of the class, and published in English.

Main Biochemistry

R.F.1:1:

1. NATURE, 1869, London, England, 14.4%, E.
2. SCIENCE, 1883, Washington, D.C., 13.0%, E.
3. JOURNAL OF BIOLOGICAL CHEMISTRY, 1905, Bethesda, M.D., U.S.A., 12.0%, E.
4. NATIONAL ACADEMY OF SCIENCES, 1915, Washington, D.C., 10.6%, E.
5. BIOCHIMICA ET BIOPHYSICA ACTA, 1947, Amsterdam, Netherlands, 10.3%, E.
6. BIOCHEMICAL JOURNAL, 1906, Colchester, England, 8.2%, E.
7. BIOCHEMICAL AND BIOPHYSICAL RESEARCH COMMUNICATIONS, 1959, New York, U.S.A., 7.0%, E.
8. BIOCHEMISTRY (U.S.), 1962, Washington, D.C., 6.5%, E.
9. ARCHIVES OF BIOCHEMISTRY AND BIOPHYSICS, 1942, New York, U.S.A., 5.6%, E.
10. EUROPEAN JOURNAL OF BIOCHEMISTRY, 1967, Berlin, W. Germany, 4.2%, E, F, G.
11. JOURNAL OF MOLECULAR BIOLOGY, 1959, London, England and New York, U.S.A., 4.1%, E, F, G.
12. FEBS LETTERS, 1968, Amsterdam, Netherlands, 4.0%, E, F, G.

Main Medicine

R.F.1:2:

1. LANCET, 1823, London, England, 7.9%, E.
2. NEW ENGLAND JOURNAL OF MEDICINE, 1828, U.S.A., 7.4%, E.
3. JOURNAL OF CLINICAL INVESTIGATION, 1924, New York, U.S.A., 6.7%, E.
4. ANNALS OF NEW YORK ACADEMY OF SCIENCE, 1877, New York, U.S.A., 6.5%, E.
5. SOCIETY FOR EXPERIMENTAL BIOLOGY AND MEDICINE, PROCEEDINGS, 1903, New York, U.S.A., 6.0%, E.
6. FEDERATION (PROCEEDINGS, ASSOCIATION OF EXPERIMENTAL BIOLOGY), 1964, New York, U.S.A., 5.4%, E.
7. JOURNAL OF THE AMERICAN MEDICAL ASSOCIATION, 1883, Chicago, Ill., 5.1%, E.

Main Medicine - Concluded

8. BRITISH MEDICAL JOURNAL, 1857, London, England, 5.0%, E.
9. AMERICAN JOURNAL OF PHYSIOLOGY: HEART AND CIRCULATORY PHYSIOLOGY, 1898, Bethesda, M.D., U.S.A., 4.6%, E.
10. JOURNAL OF EXPERIMENTAL MEDICINE, 1896, New York, U.S.A., 4.0%, E.
11. ANNALS OF INTERNAL MEDICINE, 1927, Philadelphia, P.A., U.S.A., 3.9%, E.
12. AMERICAN JOURNAL OF MEDICINE, 1946, New York, U.S.A., 3.9%, E.
13. JOURNAL OF PHYSIOLOGY, 1878, Cambridge, England, 3.8%, E.
14. ANALYTICAL BIOCHEMISTRY, 1960, New York, U.S.A., 3.4%, E.
15. JOURNAL OF IMMUNOLOGY, 1916, Baltimore, U.S.A., 3.2%, E.
16. ENDOCRINOLOGY, 1917, Baltimore, U.S.A., 3.1%, E.
17. JOURNAL OF CLINICAL ENDOCRINOLOGY AND METABOLISM, 1941, Baltimore, U.S.A., 3.0%, E.
18. ARCHIVES OF INTERNAL MEDICINE, 1908, Chicago, Ill., 3.0%, E.
19. CANCER, 1948, Philadelphia, P.A., U.S.A., 3.0%, E.
20. CIRCULATION, 1950, Dallas, Texas, 2.7%, E.
21. CIRCULATION RESEARCH, 1953, Dallas, Texas, 2.5%, E.
22. METHOD IN ENZYMOLOGY, 1955, New York, U.S.A., 2.4%, E.
23. BRAIN RESEARCH, 1966, Amsterdam, Netherlands, 2.3%, E.
24. AMERICAN JOURNAL OF CARDIOLOGY, 1958, New York, U.S.A., 1.7%, E.
25. AMERICAN HEART JOURNAL, 1925, St. Louis, M.O., U.S.A., 1.6%, E.

Main Chemistry

R.F.4:3:

1. AMERICAN CHEMICAL SOCIETY JOURNAL, 1879, Washington, D.C., 15.3%, E.
2. JOURNAL OF CHEMICAL PHYSICS, 1933, New York, U.S.A., 12.3%, E.
3. JOURNAL OF PHYSICAL CHEMISTRY, 1896, Washington, D.C., 7.8%, E.
4. JOURNAL OF ORGANIC CHEMISTRY, 1936, Washington, D.C., 6.7%, E.
5. JOURNAL OF THE CHEMICAL SOCIETY. CHEMICAL COMMUNICATIONS, 1972, London, England, 6.1%, E.
6. CANADIAN JOURNAL OF CHEMISTRY/JOURNAL CANADIEN DE CHIMIE, 1951, Ottawa, Canada, 6.0%, E, F.
7. TETRAHEDRON LETTERS, 1959, Oxford, England, 5.8%, E, F, G.
8. CHEMICAL SOCIETY OF JAPAN. BULLETIN, 1926, Tokyo, Japan, 5.5%, E, F, G.
9. CHEMISCHE BERICHTE, 1868, Deerfield Beach, Fla. and Weinheim, W. Germany, 5.4%, G (summaries in E and G).
10. ANGELWANDTE CHEMIE, 1888, Deerfield Beach, Fla. and Weinheim, W. Germany, 5.0%, G, E.

Main Chemistry - Concluded

11. HELVETICA CHIMICA ACTA, 1918, Basel, Switzerland, 4.7%, G, occasionally E, F and I.
12. TETRAHEDRON, 1957, Oxford, England, 4.6%, E, F, G.
13. INORGANIC CHEMISTRY, 1962, Washington, D.C., 4.4%, E.
14. SOCIETE CHIMIQUE DE FRANCE, BULLETIN, 1858, 3.9%, E.
15. JUSTUS LIEBIGS ANNALEN DER CHEMIE, 1832, Weinheim, W. Germany, 3.6%, G.
16. JOURNAL OF ORGANOMETALLIC CHEMISTRY, 1963, Lausanne, Switzerland, 3.0%, E, F, G (summaries in E).

Appendix II

PROPOSED PUBLICATIONS ON SCIENCE AND TECHNOLOGY INDICATORS

88-501E An Indicator of Excellence in Canadian Science

88-502E International Payments and Receipts for Technology

88-503E Technology and Commodity Trade

88-504E Patents as Indicators of Invention

88-505E Productivity, Science and Technology

88-506E A Framework for Measuring Research and Development Expenditures in Canada (published March, 1984)

88-508E Human Resources for Science and Technology in Canada

These publications will be available in French also.

Statistical reports describing activities in Canada with regards to each indicator series are being developed over the next year and are intended for annual publication by Statistics Canada.

STATISTICAL PUBLICATIONS

88-001 Science Statistics, monthly

88-201 Science and Technology Indicators, annual

88-202 Industrial Research and Development Statistics, annual

88-203 Resources for Research and Development in Canada, annual

88-204E Federal Science Activities, annual

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