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Measuring the Growth of Science

Quantitative data on a nation's research effort provide an index for its socioeconomic development.

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During the past year several countries have, for the first time, published data on their research and development expenditures. The wider comparison (*1, 2*) of this particular aspect of scientific effort which is thus made possible can be useful in framing research policies, especially of the less well developed countries. The research and development expenditure, defined as the amount of money a country spends annually to exploit and expand its research potential, is one of several rough indices, useful for making research policy decisions, which have been developed through the art of measuring science. This art is so young that every analysis of the limits of valid comparison of such new data necessarily becomes a diagnosis of its methodological growing pains. Though somewhat abstract, this diagnosis has an important bearing on the practical aspects of developing science.

Quantification and Measurement

The measurement of science is a child of our age. The social planning of policies has made quantification and measurement an indispensable tool in both the art and the science of government. This was first realized in the 17th century by one of the active participants in the intellectual phase of the scientific revolution. Sir William Petty stated then in his *Political Arithmetic* and his *Political Anatomy of Ireland* that to make practical decisions on policy matters "one had to express oneself in terms of number, weight, and measure" (*3*). In the present, or research policy, stage of the scientific revolution, to develop science into a powerful social force one must discover and learn how to use "the number, weight, and measure" appropriate to the management of research on a laboratory level, to the administration of research, and to research policy making on a national level, as well as to the disciplines in which the study of various aspects of science is undertaken for its own sake. From the published proceedings it appears that a recent conference (*4*) on the role of quantification in the history and methods of the sciences ignored the art of measuring science itself. This happened probably because serious efforts to introduce quantification and measurement in the study of the history, the sociology, and the psychology of science and in the social engineering and management of science were first made only some 15 to 20 years ago and were made quite independently in these various fields.

With growing awareness of the increased rate at which social change is brought about by science there has occurred, since 1945, a rapid growth in these disciplines—in the sociology, philosophy, psychology, and history of science. These are still more or less independent disciplines constituting what was hopefully christened some 30 years ago the "science of science" (*5*) or "metascience" (*6*). And just as engineering in the 17th century was not a deliberately "applied" science, the management of science and the engineering of science on a national level today are still too much rule-of-thumb arts, are still based too little on systematized knowledge about science as a sociological, psychological, and historical phenomenon, to warrant the name "applied science of science." At present those who are engaged in the planning or management of science and those who want to know about its various aspects are, so to speak, peeking over each other's shoulders to see what the other is doing. The current bibliographies of the respective disciplines present the following picture. The first bibliography and trend report on the sociology of science (*7*) includes not only numerous studies on the history and psychology of science but also studies on the practical problems of research policy and management of science. In any one of a number of "psychological abstracts" one can catch the "psychology of science" peeking at its sister disciplines. On the other hand, the bibliographies on current research projects on various aspects of research policy (*8*), or on the administration of science (*9*), or on the management of science (*10*) contain numerous problems from the field of the basic "science of science." Each of these disciplines is just beginning to develop a language of its own and to speak the languages of the others. But insofar as the quantification and measurement of science is concerned there seems to be little peeking, and each of these disciplines is going on its own merry way.

The managers of research, the administrators of science, the research policy makers—in other words, the

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social engineers of science—have developed a considerable activity to devise ways of applying the "number, weight, and measure" technique to science. The art of measuring the practical aspects of science is still in its infancy, however. The youth of the art of measuring the state of science on a national level is perhaps best shown by the following fact: neither the United Nations statistical publications, nor UNESCO's world survey of trends in research and its organization, and only four of 30 different national statistical books for 1960 or 1961 that I consulted in preparing this article, give any "number, weight, and measure" on scientific research. Asked for an explanation, the chief statistician of one country replied: "Our year book has no data on science because the method of measuring science itself is *everywhere* in its infancy." The data presented in this article (see Tables 1 and 2) and all other, similar quantitative indices are produced by institutions that deal with some or all of the phases of formulating and executing research policies. An analysis of the best existing summary of the present state of this art (*11*) shows that the basic difficulties in measuring the practical aspects of science are inseparable from the problem of method in the social engineering of science. The principal difficulties seem to be those of defining a system of consistent and measurable concepts that are both necessary and sufficient for all the decisions constituting a research policy, and of defining, on the basis of this system, the practical operations necessary to produce accurate and noncontradictory numerical data from actual laboratory work going on in science and from everyday work in the management and social engineering of science.

State of the Art of Measuring Science

The growing urge to engineer, to have a managerial insight into all the activities constituting science, is increasing both the demand for the appropriate "number, weight, and measure" and efforts to solve the methodological difficulties. So far, only a few of the most developed of the 110-odd independent countries of the world have assembled data for even the the roughest of the indices required for making research policy decisions. Among these indices, "research and development expenditure" seems to be the favorite at present, not only among research policy makers but also among those interested in the economic impact of research and in economic planning (*12*). So far, it seems, 20 countries have produced and published numerical data, of various degrees of reliability, on this index. By 1964, probably, data on research and development expenditure will be available for most countries of the world. Countries such as the United States, the United Kingdom, and West Germany, which began a time-series measurement of this index a few years ago, are still uncertain about the reliability of their measurements on account of the many methodological difficulties involved.

The problem of trying to determine how much of what in science was spent by whom, and for what purpose, ends at times in some chickens being counted twice and some not at all. In the United States, the nation that has the most experience in measuring the practical aspects of science, one obtains "many different estimates current for what seems to be the same or very nearly the same things"; these estimates as shown in the case of "basic research" (*13*) or of "military research and development" (*14*), can differ by as much as 300 percent.

To establish the limits of valid comparison of the data on research and development expenditure presented in this article it is necessary to take into account not only this dark side but also the bright side of the medal. First, it should be noted that most of those measuring research and development expenditure in various countries run into the same difficulties, independently of one another. They use the same methods to increase the reliability of the data, in an effort to make them comparable. They all start by defining such concepts as "research and development," "expenditure," "performers of research," and "costs to run versus costs to expand the research potential." Second, the reliability of the data increases in most cases with experience—with the number of measurements made over a period of years. Third, many of the difficulties listed do not exist in countries just starting to develop scientifically, and these are the most numerous. The less developed countries have almost no research in industrial enterprises, almost no inventors or patents, hardly any research in the universities, usually little military research, and little industrial developmental research (the last is the most costly, the hardest to define, and the most difficult to measure). In many such countries government is the sole source of funds for research, and government laboratories are the only research laboratories. One could say, therefore, that the more research activity a country has, the more difficult it is to measure it. Although the less developed countries have less experience in measuring scientific effort, their tasks are simpler, and one can easily obtain rough estimates of their research and development expenditure.

From this it can be concluded that, although it is difficult to estimate the errors, a comparison of the orders of magnitude of data on research and development expenditure and of their rough rates of change is feasible, especially since these data fall (Table 1) into three groups, each covering roughly one order of 10. One should not, therefore, yield to the temptation to compare contiguous figures such as, for example, those for Sweden and Canada or for India and Pakistan. The basic data used in this article were obtained from figures on research and development expenditures given by the official sources in each country, except for China, Yugoslavia, and the Soviet Union. The currency rate of exchange introduces another ambiguity in the data, in the case of China amounting probably to over 30 percent (*15*). All data for which no reference is given are taken from United Nations statistical publications.

Less Developed Countries as Preresearch Cultures

In spite of their ambiguity, the rough statistical data on the trends in research and development expenditure can be useful for certain research policy decisions, especially those of the less developed or underdeveloped countries. For this purpose a definition of "underdeveloped country" is used here which some find unpalatable and others consider politically dangerous but which has been proved accurate and operationally useful in social science research. The activities of decision makers in both the developed and the less developed countries, though the decision makers will hardly admit it, are based on the following definition:

An undeveloped country is an undeveloped culture. Here, *culture* is defined as "all ways of doing or thinking which men have learned or have invented." Or, in a narrower sense, "culture may, indeed, be defined as the measure of man's control over nature. . . . It is the sum total of the technical, social, and conceptual apparatus evolved in this process, that we term culture" (*16*). These definitions of culture are based on the hypothesis that at present all cultures are evolving in a planned way toward a common world culture, toward what Ritchie Calder calls a global civilization. "Development then consists in carrying out with the aid of the outside world, but primarily by their own forces, a planned, rapid and simultaneous change of most complexes of their existing cultures in the general direction of the developing world culture" (*17*). One of the distinguishing complexes of the culture of the developed countries is scientific research. For example, as a result of the scientific revolution and the economic stage that it has reached, scientific research today has become the key social force, changing production forces on a world scale. The production forces based most directly on research dictate prices and consumer demands on a world market. Consequently, the less your production processes are based on research work, the more expensive your products are in terms of human labor and the weaker your position is in both the domestic and the world market. On this law, best formulated by Marx in *Das Kapital,* are based today the actions of the more developed countries and the actions of individual firms in the private-enterprise structure of a single country. But even today there are people in the more developed countries who, when faced with the primitiveness of all aspects of life in the less developed countries, ask doubtfully, "Should such a country devote any energy to developing scientific research in the first stages of its development?" Those who ask such questions forget that the general law just given operates in the less developed as well as in the more developed countries. Thus, a country cannot begin to take the first steps in planning its development—that is, it cannot undertake a basic survey of its natural and human resources and initial conditions for development—without a minimum of research potential, domestic or borrowed from abroad. This idea, although by no means universally accepted only a few years ago, has become an axiom for action on development, as is shown by reports from numerous sources, such as, for example, the Rehovoth conference (*18*) and the United Nations conference on science and technology in the less developed countries (*19*). Furthermore, the first step in the development and exploitation of these resources requires a continuous flow of research results—at first, mostly applied research results—to achieve the sequence of goals constituting the development plan. And the most practical and least costly way to obtain them in the long run is to have a national research potential to produce these results.

From these general arguments on the present state of interaction between scientific research and society, and from the definitions of undeveloped countries and of cultural revolution that have been given, there follows one basic conclusion on national policy: The building of scientific research in the less developed countries into a social force relatively as strong as it is in the developed countries must have, from the first, a priority as high as, for example, economic development on the list of prospective tasks of the less developed countries. To be useful to the social engineers of the cultural revolution this qualitative national-policy decision should be translated into measurable concepts defined in terms of actions, men, means, and time. These indices should be related to indices for economic, educational, and other policies. In other words, the social engineers should find which measurable concepts are both necessary and sufficient as bases for all decisions constituting a research policy in general and for the research policies of the preresearch cultures in particular.

Table 1. Expenditure for research and development (*30*).

Country	Year	R&D expenditure: Percentage of gross national product (*P*)	R&D expenditure: Per inhabitant (*N*) ($)	Consumption of commercial energy per inhabitant, 1960 (kg equivalent coal) (*E*)	Rank order *N*	Rank order *E*	Approximate time lag in *N* (yr)
U.S.	1960–61	2.8	78.4	8013	1	1	0
U.S.S.R.	1960	2.3(?)	36.4	2847	2	8	5–20
U.K.	1958–59	2.5	26.0	4920	3	3	10–20
Sweden	1959	1.8	24.3	3496	4	6	10–20
Canada	1960	1.2	21.9	5679	5	2	10–20
West Germany	1959	1.4	15.7	3651	6	5	10–30
France	1961	1.3	15.2	2402	7	10	10–30
Norway	1960	0.7	10.0	2732	8	9	15–40
Australia	1960–61	0.6	8.9	3904	9	4	15–40
Japan	1960–61	1.6	6.2	1164	10	12	20–40
New Zealand	1961–62	0.3	5.3	1982	11	11	20–40
Poland	1960	0.9(?)	5.3(?)	3097	12	7	20–40
Yugoslavia	1960	0.7	1.4	858	13	13	30–50
China	1960		0.6	600	14	14	40–60
Ghana	1960	0.2	0.4	98	15	19	40–60
Lebanon	1960	0.1	0.3	596	16	15	40–60
Egypt	1960		0.3	281	17	16	40–60
Philippines	1959–60	0.1	<0.3	138	18	18	40–60
India	1959–60	0.1	<0.1	140	19	17	50–70
Pakistan	1960	0.1	<0.1	67	20	20	50–70

Measuring Socioeconomic Development

There is a growing amount of work being done to quantify the definition of less developed country by ordering all countries on a scale of indices typical of some basic culture characteristics of the more developed ones. Berry, for example, has listed 45 such numerical indices for 95 countries (*20*). All United Nations statistical publications basically measure the cultural lag of the underdeveloped countries. So far only a few culture complexes, pertaining to economy, demography, health, and education, have been thus quantized, measured, and listed. The measure of the growth of science is an essential index of the development of a country. Yet as I have stated, so far, among the numerous indices for measuring the degree of development of a country, there have been none giving in terms of men, money, time, and actions a quantified estimate of one of the most characteristic culture complexes of advanced countries: scientific research.

Table 2. Rates of growth and doubling periods of N.

Country	N_i ($)	Year	$\frac{\Delta N_i}{\Delta t} = k_i$	$\frac{I}{N_i}\frac{\Delta N_i}{\Delta t} = c_i$	Approximate doubling period of N (yr)	
					From data in Fig. 1	From $\bar{c} = 0.14$*
U.S.	78.4	1960–61	8.0	0.10	5	5
U.S.S.R.	36.4	1960	4.9	0.13	4	5
U.K.	26.0	1958–59	3.1	0.12	5	5
Canada	21.9	1960	2.3	0.11	5	5
West Germany	15.7	1959	2.3	0.15	3	5
France	15.2	1961	2.6	0.17	3	5
Norway	10.0	1960	1.6	0.16	3	5
Australia	8.9	1960–61	0.1	0.02		
Japan	6.2	1960–61	1.6	0.20	2	5
Yugoslavia	1.4	1960	0.2	0.14	3	5
China	0.6	1960	0.2	0.20	2	5
India	0.06	1960	0.01	0.17	3	5

* Average $\bar{c} = 0.14 \pm 0.05$.

Since the art of measuring science, with the aid of the art of decision making and the science of science, has devised no better index, the data on research and development expenditure are used here in estimating how powerful a social force scientific research is within each country and in drawing comparisons between various countries. For this purpose two simply related indices are used: (i) research and development expenditure as a percentage of the gross national product, P, and (ii) research and development expenditure per inhabitant N.

The values of N and P for 20 countries for which the data on research and development expenditure are available at present are given in Table 1 and in Fig. 1.

Research Policy and the Two Indices on Science

What are the research-policy conclusions one can draw from these data? There is one general conclusion to be drawn just from the number of data produced by each country, irrespective of how accurate they are. The number of data about its own science that a country produces is in itself a measure of its government's awareness of two things: of the importance of scientific research and of the necessity for a research policy based on measurement of all the appropriate aspects of science. Tables of this kind, no matter how approximate the data, do help to wake up governments to the importance of providing for adequate scientific growth. Experience has shown that a government, upon seeing its country unrepresented in such tables, tends to ask: "Where is our place among these data?" or "What is our research policy and is it adequate to our present and future needs?"

Decision makers engaged in building science are asking more and more often in private and in the public press, a very practical research policy question in quantitative terms: What percentage of its gross national product, or how much money per inhabitant, should a less developed country spend on scientific research?

Up to now two general types of suggestions have been advanced. The first considers what seems to be desirable, while the second estimates what seems to be possible. Thus, the NATO Science Committee (*21*), and a UNESCO-sponsored conference on science in Latin-American countries (*22*) both suggested in 1960, when the most developed countries were spending about 2 percent of their gross natural product on research, that a less developed country should spend at least 2 percent of its gross national product on research. On the other hand, some decision makers on science in Southeast Asia (*23*) and the Middle East (*24*) suggested recently that 1 percent of the national income should be the upper limit for the research and development expenditure in the foreseeable future. Both types of suggestions represented the rule-of-thumb, commonsense approach of practical men.

Let us consider this question now from the point of view of a nonexistent program of social engineering of science. I will start by simply analyzing the expenditure data available for a few years for 20 countries, presented in Fig. 1. I will then consider the results of this analysis in the light of the definition of underdeveloped countries as undeveloped or developing cultures.

In an earlier article (*2*) it was stated, on the basis of data for only four countries, that the higher the economic development of a country is, the greater is P, the percentage of the gross national product invested in research. As may be seen from Table 1, there is a definite positive correlation between the index P for the 20 countries and the index most generally accepted for measuring the degree of economic development—namely, the consumption of commercial energy per inhabitant. Furthermore, a rank-order correlation between the energy consumption index and N, the research and development expenditure per inhabitant, for the 20 countries in question gives a correlation coefficient of 0.88. I will broaden this hypothesis of the relation between the economic development and the amount of money spent on research by the following elementary analysis of the rate of change of N as derived from Fig. 1 and presented in Table 2.

1) The data for all countries were obtained within the same absolute period (1952–61) in the current phase of the scientific revolution, roughly for the same number of years (1 to 9). This time interval is sufficiently small for us to assume that there were no considerable changes in the research policy and the knowledge about science on which the policy was based.

2) As a rough approximation it is assumed that all the curves of Fig. 1 are straight lines of slope k_i passing through the point of maximum N_i.

3) In all the 12 cases for which data for more than 1 year are available, k_i, the slope of the line, increases with N_i. In other words, $\Delta N/\Delta t$ is a monotonously increasing function of N. From the few cases in Fig. 1, such as China, Japan, Germany, and the United States, for which data for several years are available, it may be seen that $\Delta N/\Delta t$ increases with N itself and that the assumption of paragraph 2 is valid for Δt only. Hence, we see that the more a country spends on scientific research, the greater is its increase in research and development expenditure.

4) The k_i, the slopes of the lines at N_i, are roughly proportional to N_i itself. As may be seen from Table 2, the factor of proportionality c_i is approximately constant, except for Australia. Its average value is 0.14 ± 0.05, where 0.05 is the standard deviation, calculated on the basis of all the data in Table 2.

Growth of Research Effort

From all this one finds that within the period 1952 to 1961, N, the research and development expenditure per inhabitant, varied with time exponentially for all countries, the average growth factor being $\bar{c} = 0.14$. This curve is plotted as a solid line in Fig. 2.

This seems to confirm the suggestion, put forward some years ago on the basis of a preliminary time series of data for the United States, that the research and development expenditure increases exponentially with time (*25*). Hence, it seems compatible with the known facts to say that if a time series for N is obtained for each country over a long period of time in the present stage of the scientific revolution, an exponential curve of the type given in Fig. 2 will be obtained. In other words, the absorption of research and development expenditure per inhabitant follows a "natural growth" law.

Certain other obvious conclusions follow. In spite of the ambiguities in the values of c_i it may be said that the number of years necessary for doubling of the research and development expenditure per inhabitant is roughly of the same order of magnitude for all countries, and is about 5.

These data offer a means of measuring the degree of development of a country in terms of time. If, in the curve in Fig. 2, one substitutes the actual values of c_i and N_i for each country, one obtains what can be called the "age" of each country in the present stage of the scientific revolution. This "age" is given for all countries in Table 1, column 8, expressed as the cultural time lag with respect to science. It tells us roughly that, at the present absolute rate of research and development expenditure per inhabi-

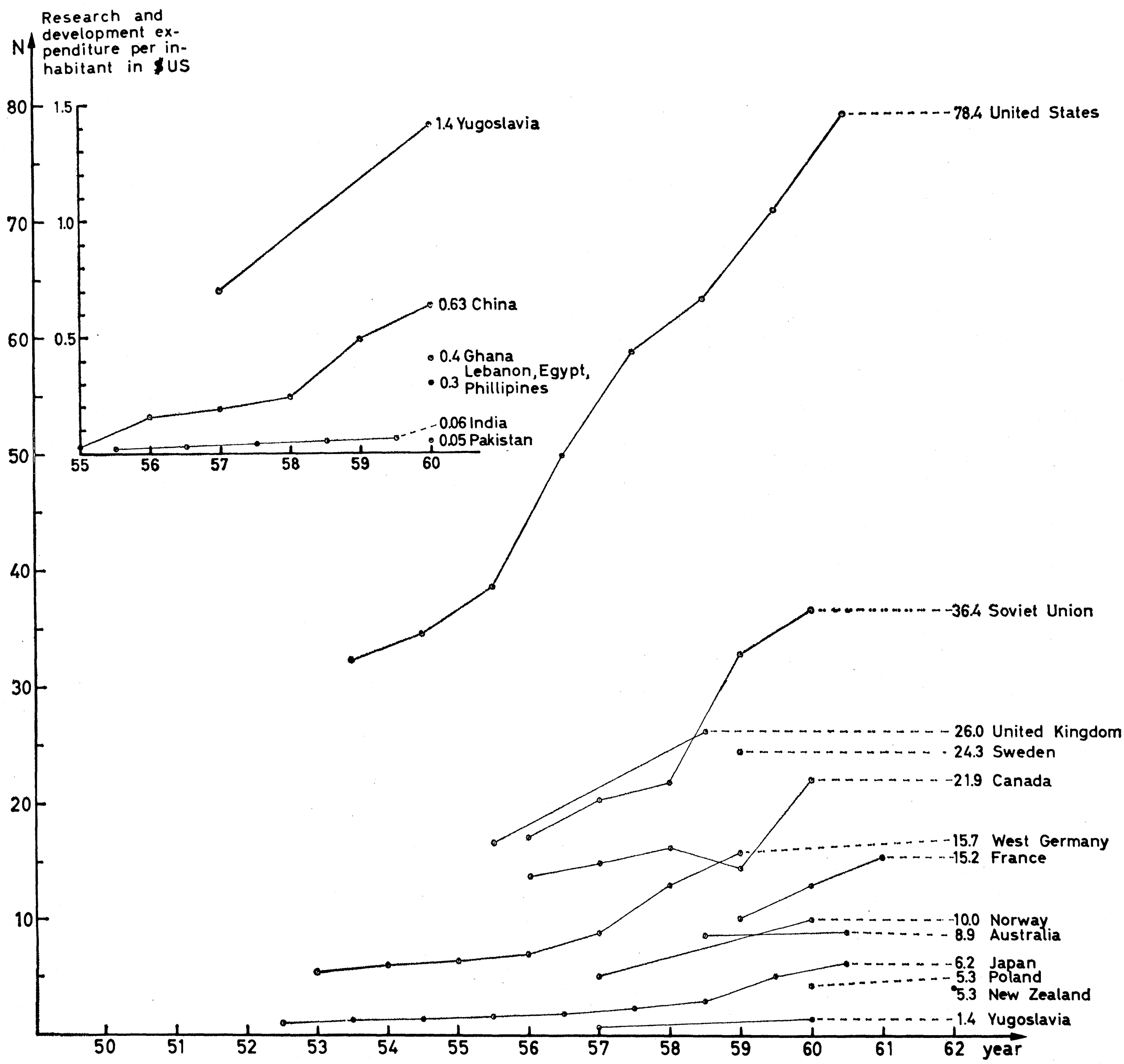

Fig. 1. Plot of the values for research and development expenditure per inhabitant from 1952 to 1961.

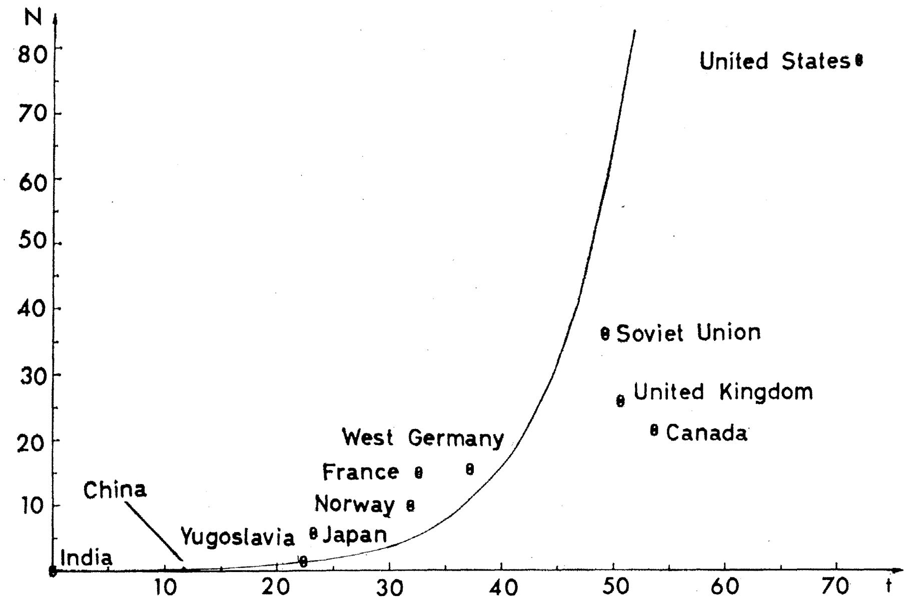

Fig. 2. Exponential growth of research and developmental expenditure per inhabitant (N) with time (solid line), the average growth factor $\bar{c} = 0.14$. The points for individual countries are plots of $N_i t_i$, where N_i is the figure for the latest available year for each country, and t_i is the relative "scientific age" (see text), obtained from the c_i (Table 2, col. 6) and N_i (Table 2, col. 3).

tant, India, for example, lags from about 50 to 70 years behind the United States.

From the data of Table 2 and Fig. 2 there appears to be a certain systematic increase of c_i with $1/N_i$. For the four countries that spend more than $20 per inhabitant, the average c is smaller than for the rest. This apparent systematic trend may be caused by a number of factors. One must not exclude, for example, the possibility that countries spending less than $20 per inhabitant have tended to overestimate their research and development expenditure. On the other hand there may be a systematic decrease in the growth of research and development expenditure with the "scientific revolution age," a trend toward decrease in the power to absorb research and development expenditure in the most developed countries.

How correct these conjectures are can be determined only from more abundant and more accurate data on N or P for a larger number of countries over a longer period of time.

Determinants of Research Effort

Here we shall consider very briefly what social factors are likely to give rise to the "natural growth" of research and development expenditure per inhabitant. The indices N (the research and development expenditure per inhabitant) and P (the percentage of the gross national product invested in research) measure, in terms of money, the scientific effort of a country, the input made to exploit and expand its current research potential. The research potential is defined and measured in terms of the number of scientists working in research or training researchers, the equipment they use, and their productivity in terms of research results and researchers trained. Hence, one must consider the relation of the research potential to the "natural growth"; one must analyze what social forces determine the rate of growth of the research potential and how one can measure them. All these questions are of fundamental importance for practical research policy conclusions. Having an answer to them, the decision makers can estimate within what limits one can plan and bring about growth of the research potential at the maximum rate of efficiency. From this estimate they can decide whether the rate of "natural growth" can be changed, and if so, by how much, and by what kind of policy decisions. They would be interested to know under what conditions and by what complex socioeconomic-political decisions a country can, if not actually "jump generations," at least "age" more rapidly as regards scientific research than the "natural" rate will permit. To begin answering these questions one must know what social forces determine the magnitude of P or N for a country at a given stage of development of its culture and how these magnitudes are related to the actual growth of scientific effort. When we rush into the domain of a problem where the economists are at present carefully treading it seems reasonable to start with the assumption that these indices are not completely independent of the degree of development of the culture and that they cannot be changed at will. A country's input into science, the magnitudes of P or N at a given stage of its development, can be said to be the resultant of mutual interaction of at least three social forces. Here "social force" is "any effective urge or impulse that leads to social action. Specifically, a social force is a consensus on the part of a sufficient number of the members of society to bring about social action or social change of some sort" (*26*). These inputs depend upon several factors.

1) The level of development of science within the country—that is, the magnitude of its research potential, as defined earlier. The rate of growth of the research potential is not independent of its size; the "research population" does not have an arbitrary rate of growth but depends in part on the size of the previous generation of scientists.

2) The demands for outputs made on the existing research potential by the industrial, agricultural, health, educational, political, intellectual, military, and other institutions, complexes, and traits of the existing culture of the country.

3) Awareness, on the part of the decision-making elite of the country, of the need for research in a modern society in general and in theirs in particular. This awareness, which can "lead to social action" in terms of policy decisions, is based on the information and knowledge the decision makers derive from two principal sources. First, this awareness is derived from the "effective urge or impulse" that stems from factors 1 and 2 —from the conclusions that the scientists and the actual or potential users of research results reach on the need for developing, and the mode of action needed to develop the research potential. Second, this awareness arises from the decision makers' own estimate of the role of research and its social effects on the country's position in the world of today and tomorrow.

The relative strengths of these social forces in determining the magnitude of

N and P for each country at a given period are hard to estimate. One can say, however, that the first two depend on certain outputs from N and P: (i) increase in the research potential; (ii) the quantity of scientific results produced; and (iii) the results obtained from i and ii by industry, agriculture, national defense, health, education, and so on. Hence, it may be concluded that the growth of science in a country depends on the linkage between the awareness, on the part of the decision makers, of the relation of the role of research to the present and future economic and social needs of the country on the one hand and the country's scientific achievement and degree of economic and social development on the other. The high rank-order correlation between N and the energy consumption per inhabitant, mentioned above, is one of innumerable possible quantitative illustrations of the validity of this conclusion.

If this strong interaction between the inputs and the outputs of research does indeed exist, how effective can we expect social action to be in fostering the growth of science? This depends, first, on the relative magnitude of the social forces determining the N and P and, second, on the knowledge and skill of the social engineers of science who undertake to use these forces to stimulate the growth of research.

In preresearch cultures the output of research results is extremely small, if there is any at all. The scientific community is almost nonexistent, or is at least nonvocal. The social utility of the research performed is extremely small. Hence, the demand for output—the second social force that determines N and P—is also practically zero. Thus, the linkage between the scientific potential, the results it produces, and the economic forces is nonexistent in preresearch cultures. The input into science in these countries is thus based principally on the decision makers' awareness, derived from abroad, of the social role of research. This awareness is often based on very superficial or entirely unrealistic estimates of the goals to be reached through research. It can, however, be a powerful force, provided it is based increasingly on systematized knowledge about the interaction of science and society. And it is only by forging this link between the actual economic forces and the forward-looking social factors on the one hand and the scientific potential on the other that effective growth of science can be fostered. Another important factor that limits effective social action in fostering the growth of science in preresearch cultures is the fact that the best-informed decision makers in such cultures not only have to build science but have to build it while fighting traditions and cultural traits often at variance with the basic requirements for research work. To overcome such resistances it is necessary to identify and describe them through social-science research and to visualize, create, and put into action in a planned way the social forces necessary to overcome them, with as little loss as possible of creative talent and material effort.

All of this presupposes the existence of an applied science of science, with its own system of ideas, its own language of quantified concepts consistent both logically and quantitatively. We may expect and hope that the practical usefulness of the art of measuring science for research policy decisions will increase as it produces more data and overcomes its first methodological growing pains. The science of science can be of considerable help in systematizing the basic concepts of the social engineering of science. The recent work of Price (*27*) on quantification and measurement in the study of the history of science points out the utility of this kind of approach. Price starts from the fact that "the history of science differs remarkably from all other branches of history, being singled out by virtue of its much more orderly array of materials and also by the objective criteria which exist for the facts of science but not necessarily for the facts of other history," and says, "Since such oddities exist, however, it is useful to stretch the method to the full and examine critically any benefit which might thereby accrue." From the data on the number of scientific reviews, papers, researchers, and scientific institutions since the 17th century, Price has deduced intriguing mathematical regularities. The practical utility of the results of quantification and measurement in the history of science is perhaps best illustrated by the fact that, in dealing, for example, with "problems of Big Science" (*28*) or with "the main trends of inquiry in the field of the natural sciences, the dissemination of scientific knowledge, and the application of such knowledge for peaceful ends" (*29*), practical advisers on national and international research policy use the results of Price's work.

Looking, in the light of all this, at the methodological difficulties in the art of measuring the practical aspects of science—whether it is a question of management, on a laboratory scale, or policy making, on a national scale—one wonders whether an organized exchange of ideas and findings on the measurement of science between those working in the "basic" and those working in the "applied" science of science might not advance the methods of all these disciplines. After all, although pursuing different goals, workers in all of these disciplines study various aspects of a single phenomenon—scientific research.

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Are Logic and Mathematics Identical?

An old thesis of Russell's is reexamined in the light of subsequent developments in mathematical logic.

Leon Henkin

It was 24 years ago that I entered Columbia College as a freshman and discovered the subject of logic. I can recall well the particular circumstance which led to this discovery.

One day I was browsing in the library and came across a little volume by Bertrand Russell entitled *Mysticism and Logic*. At that time, barely 16, I fancied myself something of a mystic. Like many young people of that age I was filled with new emotions strongly felt. It was natural that any reflective attention should be largely occupied with these, and that this preoccupation should give a color and poignancy to experience which found sympathetic reflection in the writings of men of mystical bent.

Having heard that Russell was a logician I inferred from the title of his work that his purpose was to contrast mysticism with logic in order to exalt the latter at the expense of the former, and I determined to read the essay in order to refute it. But I discovered something quite different from what I had imagined. Indeed, contrasting aspects of mysticism and logic were delineated by Russell, but his thesis was that each had a proper and important place in the totality of human experience, and his interest was to define these and to exhibit their interdependence rather than to select one as superior to the other. I was disarmed, I was delighted with Russell's lucent and persuasive style, I began avidly to read his other works, and was soon caught up with logical concepts which have continued to occupy at least a portion of my attention ever since.

Bertrand Russell was a great popularizer of ideas, abstract as well as concrete. Probably many of you have been afforded an introduction to mathematical logic through his writings, and perhaps some have even been led to the point of peeping into the formidable *Principia Mathematica* which he wrote with Alfred Whitehead about 1910. You will recall, then, the astonishing contention with which he shocked the mathematical world of that time—namely, that all of mathematics was nothing but logic. Mathematicians were generally puzzled by this radical thesis. Really, very few understood at all what Russell had in mind. Nevertheless, they vehemently opposed the idea.

This is readily understandable when you recall that a companion thesis of Russell's was that logic is purely tautological and has really no content whatever. Mathematicians, being adept at putting 2 and 2 together, quickly inferred that Russell meant to say that all mathematical propositions are completely devoid of content, and from this it was a simple matter to pass to the supposition that he held all mathematics to be entirely without value. *Aux armes, citoyens du monde mathématique!*

Half a century has elapsed since this gross misinterpretation of Russell's provocative enunciation. These 50 years have seen a great acceleration and broadening of logical research. And so it seems to me appropriate to seek a reassessment of Russell's thesis in the light of subsequent development.

Definitions and Proofs

In order to explain how Russell came to hold the view that all of mathematics is nothing but logic, it is necessary to go back and discuss two important complexes of ideas which had been developed in the decades before Russell came into the field. The first of these was a systematic reduction of all the concepts of mathematics to a small number of them. This process of reduction had indeed been going on for a very long time. As far

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