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PRODUCTIVITY OF SCIENCE IN A SOCIETY

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THE PRODUCTIVITY OF SCIENCE IN A SOCIETY

by

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A B S T R A C T

An attempt is made to analyse the role of science as a technique in the three activities of a society, the universities, industry and government, in all of which it plays an important part. The function of science in each activity is examined with the aim of relating an input investment associated with science to the characteristic output of the activity. Productivity is discussed in each activity as the ratio of this input investment to the final output as far as these can be directly related. It is shown that each of these three activities is closely coupled together by feedback loops which can either increase or decrease the activity depending on whether they are positive or negative. Furthermore the three activities are part of the society and couple with it and nowadays industrial societies are themselves closely coupled together so that the behaviour of one affects the others. Some of the implications of these coupling loops are discussed.

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INTRODUCTION

The productivity of an activity is usually expressed as a ratio of an output generated by the activity and the relevant input which sustains it. Sometimes productivity is measured in incremental terms but whichever definition is used it is necessary to relate an input to an output and the difficulty in applying this notion to science is that science, generally speaking, is part of some other activity whose output, although dependent on the investment input to the associated science, is also dependent on other factors. Therefore in considering the productivity of science in society, it is first necessary to set forth those social activities in which science plays an important part and then to relate the input to the science component of the activity to the output of the activity as a whole either in absolute or incremental terms. It is no doubt possible to divide and subdivide almost indefinitely the activities of society in which science plays a part, but for the purpose of this paper, which makes no pretence at quantitative analysis, it is sufficient to take the very broadest of divisions and to consider science in industry, in universities and in government. Taking each of these main social activities in turn we need to determine its principal output, its inputs, particularly those associated with science, the relationships between the science input and the principal output, the criteria commonly applied to determine the scientific part of the activity and finally the factors governing its productivity and the units by which it can be measured. Needless to say, the answers to this formidable list of questions are by no means common knowledge, if indeed they are known at all, and the main purpose of this paper is therefore more to encourage methodical thinking about this problem than to review current thoughts.

Before embarking on this task it is worth noting that this way of attempting to evaluate science as part of social activities makes the implicit assumption that science is a technique which the component parts of a society have found by experience to be useful and sometimes essential in order to achieve their aims. As society has developed it has constantly discovered new techniques and discarded old ones but at the present time the technique of modern science is in the ascendancy, gradually displacing older techniques in ever increasing areas of social activities. For example science, in the sense used in this paper, is a technique for finding out more about the natural world. It is useful and occasionally essential as a technique for improving the operations of industry and nations now find it indispensable as a technique for achieving their ends and displaying to others their peculiar cultures. A technique is not an end in itself and this view of science as a means to the diverse ends of a modern industrial society rather than as an end in itself is only one aspect of science. It may be that society as it develops will find new techniques more effective than science for the achievement of its ends or maybe society will change its aims and need less science to achieve them. Whether or not science as a highly successful technique for understanding the natural world will ever be surpassed is perhaps more questionable but then in its modern form it has been employed only for the last 400 years and that is a relatively short time in the history of human societies. In this paper I shall discuss in turn the three social activities in which, at least at the present time, science is increasingly playing an important role.

UNIVERSITY SCIENCE

The unique output of universities is trained graduates and, since we are here concerned only with science, it is the trained scientist output which is of interest. There is also an output of new scientific knowledge and there is a wealth of existing knowledge maintained in the university system. The inputs to the system are money, mainly derived these days from governments, and school leavers coming from the earlier part of the education system. Just as the school leaver input to the university system couples it to other parts of the education system so there are other feedback loops from the university system to the rest of the education system, for example university graduates becoming school teachers, which make it perilous to consider the university system in isolation from the rest. We are concerned here with a closely coupled system with feedback loops and natural time constants which determine the speed and the manner in which it responds to external stimuli.

The trained scientist output of the university system is absorbed by industry, government and the rest of society and a part of it migrates to other societies, sometimes never to return. At the present time, due to the demands of the other parts of society, there is great pressure on the university system to produce more trained scientists. This in turn puts pressure on the school system to increase its output of school leavers opting to study science in universities and even the school leaver output going directly into society must these days be better trained in science. A pressure is then put back on the university system to produce more graduate scientists opting to become school teachers and one of the loops in the education system is completed.

The money input to the university system can be divided into two parts, the teaching money and the research money. Increases in teaching money are necessary in order to increase the trained scientist output and improvements in the productivity (teaching money expended per trained scientist output and teaching effort expended per trained scientist output) also will increase the output for the same input. The research money input is related to the knowledge output and it is generally recognised that this money input also determines to some extent the trained scientist output. This cross coupling between the two money inputs comes about firstly because university lecturers who produce the science graduate output assert that they must engage in scientific research in order to teach at university level and secondly because university science lecturers are usually appointed after a research period in the university system. Hence more research money is needed to produce more university lecturers and further research money is needed to maintain them as competent lecturers. Therefore in order to produce more science graduates not only must the teaching money be increased but also the research money. This process illustrates a feedback loop in the university system.

To complete this brief sketch of university science we finally come to the knowledge output. Traditionally, knowledge gained in university science is published and is available to anybody who can make use of it. It does not therefore belong to the society in which it is generated and, since most societies these days behave in the same way, there is an input of new knowledge coming from all societies to any particular society which the other societies have paid for. Therefore in contrast to the trained scientist output, which is largely absorbed by the society in which it is generated, the knowledge output is more in the nature of a contribution which a developed society makes to a commonwealth of knowledge of all societies and, perhaps for this reason, the research money input which supports this output is often related to the relative wealth of a particular society. This free flow of new knowledge between societies is advantageous to the smaller societies who gain most from the contributions made by the larger societies, their only restriction being the ability to make use of the new knowledge. However, relating the research money input to the wealth of the society in which the knowledge output is generated overlooks the strong coupling, already mentioned, between the research money input and the trained scientist output. If the aim of a society is to produce more trained scientists for its own consumption, failure to increase the research money as well as the teaching money can result in a shortage of university lecturers and hence an inability in the university system to produce more trained scientists. Indeed it has been observed that lack of research money causes a migration of university scientists which further weakens the productiveness of the university system. What a society loses by this migration is not the new knowledge which the migrating scientists would have produced had they stayed (that they will produce anyway wherever they are going and they will publish it) but rather the new trained scientists they would have produced and the inspiration and guidance they would have given them.

The criteria applied to the new knowledge part of university science are the familiar internal criteria of scientific research such as the ripeness of the field for exploitation and the availability of first-rate research scientists with creative ideas for making new advances in the subject. These are the criteria used by committees awarding research grants and are often referred to as the "judgement by peers". Publication of the research results and subsequent criticism impose other harsh judgements on the quality of this output. It is generally recognised that these criteria have maintained the quality of the new knowledge output of universities in all societies at the highest levels. The criteria applied to the trained scientist output of university science are, on the one hand, another form of "judgement by peers" through the examination system which maintains the quality of this output and, on the other hand, criteria to do with the relevance of this output to the needs of society, and it is the second of these criteria which are being much discussed these days. The university system and indeed the whole education system differs from other productive activities in a society in that the customers for its principal output do not directly pay for the goods they receive and hence they only indirectly influence the product. Nowadays it is governments who mainly finance the university system and the trained scientists at graduate and post-graduate levels are absorbed by industry, government and the rest of the activities in the society. In terms of social engineering one should aim to match the trained scientist output of university science to the current needs of the various activities of the society and plan to keep it matched with the changing needs of society. The question is who should control the output mix. Should it be the governments who largely pay for it or the universities who produce it, or industry and the other activities of society who use it, or should it be some combination of all interested parties? At the present time it is the universities, responding to market pressures to a greater or lesser extent, who mainly determine the output mix although it is becoming apparent that the personal choices of school leavers are also having a marked effect.

We come now to the productivity of university science and how it should be measured. As far as a particular society is concerned the essential output of its university science is the trained scientist output. In a modern industrial society this is the lifeblood of the society and if it becomes insufficient in quantity or lacking in quality the survival of the society is placed in jeopardy. The new knowledge output is of less importance in this respect since if it were zero in one of the smaller industrial countries the total influx of new knowledge from all other societies to that society would hardly be affected. Nevertheless the new knowledge output is of vital importance to a society in that the research money input which sustains it determines the quality and quantity of university teaching and hence directly affects the quality and quantity of the trained scientist output. Furthermore the research money input when divided into support for the different disciplines of science offers a way of controlling the output mix of the trained scientists and hence assists the matching of this output to the needs of society. For example, a society needing more physicists or more chemists in its industrial activities could make available to its universities more research money for these disciplines leaving it to the well tried internal criteria of science to determine how it was distributed. There are two other respects in which the new knowledge output from university science is relevant. Firstly a society in which little new knowledge is produced could become in course of time unable to use the new knowledge generated by other societies and secondly the ability to generate new knowledge is in itself a manifestation of the vitality of the society and of its cultural level and aspirations. Although one cannot perhaps quantify these matters they undoubtedly affect the attractiveness of that society to its most creative citizens and to similar people from other societies. In a world which is rapidly shrinking it pays a society to be as attractive as possible to creative people.

In measuring the productivity of university science it seems then that the relevant output is the trained scientists and the input is the money for both teaching and research. The output mix of trained scientists should be kept in step with the needs of the society in which they are produced.

INDUSTRIAL SCIENCE

The inputs to industrial science are trained scientists from university science and money from profits made through the operations of industry. The outputs become manifest in improvements in the goods or services produced by industry which produce more profit to the industry. Industrial science, in the sense that the term science is being used in this paper, affects all the operations of industry from research and development through design and production to marketing and management. Therefore improvements in the goods or services due to industrial science can and do occur in all industrial operations. The difficulty in relating inputs to outputs is to trace an input through to a measurable output since many factors apart from industrial science affect the final product and its saleability. Although several attempts have been made to relate input to output by historical studies of particular industries and products there are at present only rough criteria available to industry. One general observation is that as time goes on industrial goods and services steadily become more sophisticated scientifically and technologically and this is reflected in increasing demands by industry for more trained scientists and more scientific training for all its employees. This trend seems to be built into the industrial competitive system and it is accelerated by advertisement which constantly stimulates consumers to demand increasing technological sophistication in the goods and services provided by industry. All the loops in industrial activity seem to provide positive feedback which increases the amount of industrial science and cause it to increase its demand on the principal output of university science. If industry had to pay for trained scientists this would provide some negative feedback limiting the rate of increasing scientific and technological sophistication in industrial goods and services but this is not the case. Nevertheless this input is beginning to limit industry in all societies not because the cost per trained scientist to industry is increasing but because it is becoming difficult for university science to increase its output. Since it is governments which largely finance the production of trained scientists by universities they effectively control the rate at which this output increases with time and hence they determine to a large extent the competitiveness of their own industry in so far as it is affected by industrial science rather than by other factors. Governments in turn derive their money from the society they represent and the wealth of that society if it is an industrial one depends on the competitiveness of its industrial component. Thus the loop is finally completed but it is rather a long one.

In general the criterion applied to industrial science is that it should increase the profitability of the industry. Where there are alternative ways of achieving that objective, industrial science must demonstrate that its way leads to the highest profits. In design, production and management the ways of industrial science are steadily gaining ground and "commercial criteria" can be applied, but in the research and development field it is more difficult to apply these judgements and other relationships are being developed. For example the amount of investment in research and development activity in an industry is related to the rate of change of its product with time. Those industries with a product which changes slowly with time need less research and development investment than those with a fast changing product. This relationship enables an industry to use its research and development investment as a weapon in competition with other industries, either offensively to gain supremacy, or defensively to stay in business. There is therefore a threshold amount of research and development investment below which an industry cannot survive and this threshold level depends on the particular products of the industry. Pooling research and development activity amongst like industries is only effective if individual industries can get their work done on a strictly confidential basis otherwise they cannot use research and development as a weapon in competition. Furthermore the fruits of research and development are a saleable commodity and can be bought by licence or stolen by industrial espionage. These and other relationships are beginning to be understood these days and it should be possible finally for an industry to determine the level of research and development appropriate to its products, its current competitive position and its strategy for the future. Whatever emerges from these studies it is however likely that commercial criteria will always favour the shorter term research and development activity where the effect on the product can most easily be traced back to the original investment. This means that long term research and development aimed at, for example, a new power source for a society or at a completely new communications system must depend for its support on funds other than the profits of individual industries unless of course single industries, by successive mergers, finally grow to the size of present day nations. This suggests that the duration of research and development projects depends on the size of the organisation whether it is a society or an industry. The larger the organisation the longer term research and development projects it can attempt.

GOVERNMENT SCIENCE

The inputs to government science are trained scientists and money derived by the government from the society by taxation. The outputs are 'missions' or national technological goals and scientific and technological services required by the society or component parts of it. Thus it is the function of government to determine the aims, ambitions and needs of the society it represents and it is the function of government science to achieve them. Military missions were probably the first and still are the dominant scientific and technological goals of modern industrial societies and they account for the biggest share of the investment in government science. However new missions, not unconnected with military ones but non-military in aim, have developed since the last war. Nuclear energy and space exploration are typical examples,and the civil parts of these technological programmes now account for sizable fractions of government science investment. Nowadays new national technological goals are being considered and started which arise from aims and ambitions of societies quite different from military ones such as the need for integrated transport systems and new transport methods for goods and people and the interest in the natural environment both to exploit it more fully and to protect it from the pollution of industrial societies. Benefit to the society as a whole rather than profit to individual industries is the criterion generally applied to these missions although in the long term it is sometimes possible to show economic gains.

Government science is a self limiting system in the sense that the wealth of a society, both in manpower and money, must ultimately limit its aims and ambitions. Also by absorbing part of the trained scientist output of the university system, whether by employing them directly in government laboratories or indirectly in industry and universities by way of agency contracts, government science, especially when there is a shortage of trained scientists, appears to decrease the productivity of its industries and reduce the available wealth of industrial societies. However the effects of this negative feedback loop are balanced, some would say more than balanced, by the positive effects of government science on industrial performance and competitiveness. National technological goals of the kind mentioned above are difficult and challenging scientifically and technologically and the stimulus they have given to industry has been immense. In some cases completely new major industries have come into existence which now account for a large part of the employment in modern societies. Even more important, industries new and old have been able to establish production facilities for new and improved products to satisfy government agency demands so that when commercial markets for these products finally emerged these industries have been able to sweep in to satisfy them. Thus industries in those societies with the more ambitious goals have not only been stimulated to make rapid technological changes but also they have acquired considerable lead times in production which have greatly improved their competitiveness and similar industries in less ambitious societies have found their competitive position correspondingly worsened. Furthermore it has turned out that ambitious national goals attract scientists and technologists from other societies thus further weakening the competitiveness of the industries in those societies. A solution to this dilemma for the smaller industrial societies is for them to join together into societies of a size comparable with the largest so that they can support equally ambitious and exciting, but not necessarily identical, technological goals. This is not a question of keeping up with the Jones's for reasons of national pride or dignity but a question of economic survival in the long term.

Government science, especially the mission oriented part, can either be carried out in whole or in part in government laboratories or contracted out to industry and to the universities but whichever method is adopted for the research and development component the manufacturing part of the mission is normally undertaken by industry. Societies differ in the amount of research and development carried out in government laboratories. In America the practice is to use industry and universities for a large part of this work whereas in Europe and particularly in Britain more is carried out in government laboratories. The advantage of using industry for this work is that the research and development flows naturally through into design and manufacture and any commercial 'fall out' from the work can quickly be taken up by the industry. Similarly the advantage of using universities for government research and development is that the young scientists by partaking in this kind of work whilst at university are more familiar with the work they will be asked to undertake when they take up employment in the society. The disadvantages of using industry and universities are that the criteria appropriate for government missions ("agency criteria") are very different from the commercial criteria of industrial science and from the criteria of university science. By imposing agency criteria on the other two bodies governments can distort the proper functioning and the productivity of those bodies and make them too dependent on agency contracts and too mindful of agency criteria to the detriment of their own. It is a nice question whether the advantages of governments contracting industry and universities for mission-oriented research and development outweigh the disadvantages.

Concluding this commentary on government science it is worth emphasising that the criteria of government science are essentially political in nature. Decisions such as putting an American on the moon are taken by politicians for political reasons and it could hardly be otherwise. Productivity in government science is measured in terms of the cost in manpower and money expended to attain the mission. If the aim of the mission is economic in character then cost-benefit analyses can be used provided the time scale of the mission is not too long.

CONCLUSION

By dividing the activities of society in which science plays an important part into three broad areas and by discussing the role of science as a technique in each area it has been possible to trace some relationships between the inputs, usually trained scientists and money, to the outputs of the three activities. The outputs of each area of activity are different and the criteria used to judge the performance of science in each area are also different. It has also been possible in a rough way to suggest measures of productivity and again they are different in the three areas. Particular emphasis has been laid on loops in the system both within the particular activities and coupling the three activities together. The importance to the whole system of whether the loops are feeding back positively or negatively has been discussed. If it were possible to develop a computable model of the three activities, as is now being done for complete education systems, and relate it to an economic model of the whole society of which they are a part, one could learn better how the complete system works and experiment with changes in the feedback loops. Lacking such a model one can only observe and analyse the existing system and try to deduce what effect possible changes might make. Such a procedure can hardly be called a science since real experiments are impractical and without them theories cannot be checked. Furthermore the time constants of the system and its component parts are very long - several years, even decades - so that controlled experiments, even if practical and tolerated by society, would be extremely difficult. Nevertheless a methodical approach to the problem is probably better than wild surmise.

Some general comments about the coupling between university, industrial and government science and the society in which they are embedded may be appropriate in conclusion. A scientist looking at these different activities of society in which science is playing such an important role and observing the feedback loops between them naturally wonders what is driving the whole system. There is a tendency these days to think that science somehow is the driving force and this finds popular expression in the current anxieties about science budgets and the way they are increasing exponentially with time. But if science is a technique and only a means to an end something other than science must be determining the ends. Undoubtedly science is a very popular technique and a very successful one but if we could, for example, find out more about the natural world and at less cost by means other than science it is very likely we would be using them. Similarly if industry could manufacture goods and provide services and sell them profitably to society without using science, or by employing a different and cheaper technique, commercial criteria would insist that it did so. And if governments found a cheaper non-scientific way of satisfying the aims and ambitions of the societies they represent, clearly less science and fewer scientists would be required. Whatever is said about science lobbies and their effect on governments, science cannot be the primary driving force in the system. Rather it seems that the drive comes from society itself and from its latent ambitions which science now enables it to realise. Probably all societies have similar aims and ambitions but the larger and more wealthy societies can realise the most and they can tackle the most challenging and exciting missions. If there were no interactions between societies or if the ambitions of a society did not affect the competitive power of its industry and attract to it essential elements of the population of other societies, the behaviour of one society might invoke jealousy or envy in another but it would not affect it economically. However these couplings do exist and the smaller industrial societies are learning to pay serious attention to them.

In any society, whatever its size, there must ultimately be a limit to the amount of science used. If science continues to be a most successful technique for improving industrial profits, for increasing the wealth of a society and for satisfying its aims and ambitions, science budgets are not likely to be the real limit. It is more likely that scientific and technological manpower will finally set the bounds since, however efficient the education system, there must be some limit to the natural abilities and aptitudes of a population. When these are fully realised in a particular society it can only proceed further by attracting this essential manpower from its neighbours and even this becomes economically questionable if in the long term the most attractive societies find themselves having to support the rest.