*On Institutions That Produce and Disseminate Knowledge**

by

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* We have benefited greatly from extended discussions with Paul David. As mentioned in the text, we have made liberal use of the ideas developed in Dasgupta and David (1987, 1994).

Abstract

This paper investigates institutions for the creation and transmission of knowledge as efficient resource allocation mechanisms. By looking at Science and Technology it develops a two way clasification. Science, is a non market allocation mechanism, where knowledge is treated as a pure public good and where the rule of priority provides an incentive scheme for disclosure. Technology, is a market allocation mechanism, where knowledge is treated as a private good and where patents and copyrights preserve property rights. The distinction between these two entities is based on the institutional arrangements involving the allocation of resources for enquiry, not on the differences in the objects and methods of inquiry. The paper compares the rule of priority and paptenting as alternative incentive schemes. It also discusses whether it is optimal for society to preserve two different institutions, partly rival and partly complementary, and examines the major policy implications.

Contents

1. Introduction

If sociologists and historians of science have studied the character of scientific activity, economists have investigated the preoccupations of technologists. There is now a large and impressive literature describing and explaining the dynamics of both technological change and scientific progress; but apart from a few exceptions (e.g. Dasgupta and David, 1987, 1994), we have a picture of each in isolation. It has been uncommon to relate the two, to see them at once as endeavours in the production, dissemination, and use of knowledge.

In this paper, we will view Science and Technology as institutions, each with its own implicit goals. The distinction to be drawn here will be based on a difference in the institutions' objectives. From this vantage we will attempt to explain differences in their norms, practices, products, and in the codes of conduct among their members. These latter differences have been much noted in the literature. Thus, by capitalising the terms Science and Technology, we are indicating that the distinction between the two entities should be based, not on the types of knowledge they produce, nor on the methods of inquiry they adopt; but rather, on differences in the institutional arrangements involving the allocation of resources for inquiry. Differences in what is produced within these institutions and on the methods of inquiry they adopt can then be explained by differences in institutional arrangements, they won't need to be the defining characteristics of the institutions.

We believe that the approach pursued here can also be of help in distinguishing the Arts from the Crafts. So, on occasion we will allude to them in what follows. But our understanding of the Arts and Crafts is very much less than expert. For this reason we will focus on Science and Technology.

Any such classification as we will present has to be drawn in broad strokes, and there are many examples that do not quite fit. But the point of view we will adopt here explains several phenomena occurring in both Science and Technology that are puzzling. It also has implications for policy. In particular, it helps explain why the position of Science in modern societies is at once exalted and financially so precarious as to require constant public nurturing. Our viewpoint will show that Science and Technology have not only a symbiotic relationship with each other, but that the two entities assume adversarial roles as well. There are disquieting signs today that this latter relationship has become dominant, that Science as a distinct social entity is in danger of being undermined by the technological community's conception of knowledge as a form of productive capital. The danger is acute, because this conception is increasingly being shared by governments.[1]

The word knowledge is the key common ground of the two social entities. For reasons of space, we will assume for the greater part that both Science and Technology are concerned with the production, dissemination, and use of what has elsewhere (Polanyi, 1966) been called codified, as opposed to tacit, knowledge (see below). But it is as well to bear in mind that the extent to which knowledge is codified (and, by implication, the extent to which it remains in a tacit form) is something that the viewpoint we will develop here should help explain.[2]

Scientists and technologists have usually been distinguished by the type of knowledge they are engaged in producing (e.g. general principles versus practical devices). At times they have been distinguished by their relative interests in the financial gain that their work could be expected to yield; and sometimes, by their attitudes towards the risk and uncertainty that surround the characteristics of the output of research (e.g. research completion time). On occasion, scientists and technologists have been distinguished by the sources that finance their work (public versus private); and at times, by their institutional affiliation (e.g. academic versus commercial). These are interesting approaches, but they are unduly limiting. If scientists and technologists on the whole do produce different kinds of knowledge, we should ask why they do so. If they display different attitudes towards risk and research completion times, we must seek reasons for this. If they draw upon separate sources of finance, we should be prepared to ask what it is about them that results in their not receiving support from the same source. And finally, if scientists and technologists on the whole do possess distinct institutional affiliations, we ought to study the institutional differences. These various conceptions will be reviewed in Sections 3 and 4.

Research and development (the activities that are instrumental in the production of knowledge) involve a resource allocation problem. The natural starting point is to study the distinctive characteristics of the commodity that both scientists and technologists are engaged in producing; namely, knowledge. For if knowledge were an ordinary, mundane commodity, like cheese or wine, we would have had neither Science nor Technology. In Section 2 we will identify these special features, and in Sections 3 and 4 we will ask what economics has to say about the characteristics of resource allocation mechanisms that can in principle be relied upon to generate and diffuse knowledge in an efficient manner. In Section 6 we will present a

[1] Dasgupta and David (1987) have developed this line of worry in some detail.
[2] Dasgupta and David (1994) have offered an account of this.

conceptual framework for studying science and technology which offers certain advantages over the existing ones that are reviewed in Section 5. Following the approach taken in the original statement of these ideas (Dasgupta and David, 1987), the arguments in Section 6 will be analytical.

This conceptual framework will be further elaborated upon in Section 7, where we will present an account of the structure of incentives (in particular, rules of priority and patents) that the two institutions have established for the producers of knowledge. Although informal, the account will be informed by the modern theory of organisation (e.g. Arrow, 1974; Hart and Holmström, 1988). This theory sees institutions as social structures that implement ways of reducing the inefficiencies in resource allocation arising from two facts: (i) not everyone can observe, know, and verify the same things, and (ii) contracts as a matter of practical necessity are specified less completely than they would be under ideal circumstances.

Finally in the concluding section 8 we will discuss why institutions for the creation and the diffusion of knowledge are not always efficient, and the role for policy.

2. Episteme vs. Techne

The word <u>science</u> means <u>knowledge</u> in Latin, but much thought has been given to creating hierarchies of knowledge in which a place is reserved for science in the uppermost branches. Thus, medieval Western scholars drew a distinction between speculative, theoretical, or abstract knowledge, and art or practical knowledge. The former was referred to as <u>episteme</u>, the latter as <u>techne</u>. Here, as elsewhere, they followed Aristotle. There are distinct caste-overtones in this treatment, for Aristotle thought it impolite to discuss <u>techne</u>, even to enumerate achievements in this sphere. His discourse concentrated on <u>episteme</u>.[3] This dualism is not restricted to Classical Greece, and caste-overtones can work in the opposite direction too. Indeed, most societies would appear not to have found a happy meeting of minds between the two.

Research and development (the activities that are instrumental in the production of knowledge) involve a resource allocation problem. The natural starting point is to study the distinctive characteristics of the commodity that both scientists and technologists are engaged in producing; namely, knowledge. For if knowledge were an ordinary, mundane commodity, like cheese or wine, we would have had neither Science nor Technology. So, we begin with a review of those characteristics of knowledge that are relevant for our investigation.

[3] For an account of the underlying causes and the implications of this attitude, see Finley (1965).

Knowledge is not a homogeneous, but a differentiated, commodity: there are different kinds of knowledge. There are also no obvious natural units in which knowledge can be measured. Nevertheless, it is possible to appeal to economic theory and seek an account of the forces that influence its production, dissemination, and use.

It will prove useful to draw the now-familiar distinction between tacit and codified knowledge. Tacit knowledge refers to a fact of common perception, that we are often generally aware of certain objects without being focused on them (see Polanyi, 1966). They form the context which makes focused perception possible, understandable, and productive. Even Science and Technology, let alone the Arts and Crafts, draw upon skills and techniques (the ingredients of "expertise") that are acquired experientially, and are transformed by demonstration, personal instruction, and provision of expert services (viz. advice, consultation, and so forth), rather than being reduced to conscious and codified methods of procedures. As a rule, this transfer process itself is a costly affair for both the provider and the recipient. But this does not prevent tacit knowledge from being purchased and sold. Indeed, transactions in it can resemble "gift exchanges" (Hagström, 1965), but they often involve financial transfers. In the extreme are types of knowledge that simply cannot be communicated. These include, for example, problem-solving skills (Kuhn, 1970, p.44). Such knowledge is embodied in the researcher, and should be called the researcher's skill (his innate or acquired ability).

In contrast, codified knowledge is knowledge that has been reduced and converted into messages that can be easily communicated. Codification is a step in the process of reduction and conversion, which renders the transmission, verification, storage, and reproduction of knowledge all the less costly.[4] This transformation (which itself involves the use of resources) makes knowledge at once more of a non-rival good. Thus, if person A were to give person B a piece of information, it would not reduce the amount of information possessed by A; although of course, the benefit to each would depend upon whether, and in what manner, B were to make use of the information. In short, codified knowledge can be possessed and used jointly by as many as care to do so. It follows that codified knowledge has one of the two hallmarks of a public good: it can be used jointly.[5] The other hallmark of a public good -- that once it is produced, it is not possible to exclude anyone from using it -- is not a feature of even codified knowledge; for patents, copyrights, and secrecy are ways by which people can be

[4] This usage is related to, but does not carry the broader implications of, the concept of codification in Science, as developed by Zuckerman and Merton (1972).

[5] This observation was the starting point of Kenneth Arrow's classic analysis of the economics of inventions. See Arrow (1962).

excluded (see below). Contrary to what is often suggested, even codified knowledge is not a public good.[6]

Until we say otherwise, we will focus on codified knowledge here, and we will call it "knowledge" or "information" for short. We will also, initially, assume that the cost of transmitting knowledge is negligible when compared to the cost of production. This is on occasion a good approximation, but often not.[7] Section 3 discusses the implications of costly transmission of knowledge.

We note next that the use of knowledge is subject to certain indivisibilities, in that once a piece of knowledge has been acquired, there is no social value added in acquiring it again: the wheel does not need to invented twice. The same piece of information can be used over and over again, at no extra cost.[8] In other words, knowledge is a durable good, albeit a special kind of durable good, in that, like "trust", it tends to grow with use (one's understanding of a piece of information often increases with its use), and decays with disuse.

Knowledge is frequently both a consumption and a capital good. A mathematical theorem, for example, is valued for its beauty, as well as for its ability to generate further theorems. Indeed, the mathematician's aesthetic sense may impart to a theorem the attribute of beauty on account of its fecundity. Knowledge is unusual in this respect: its productivity can confer upon it an intrinsic worth. Often enough, knowledge is a pure capital good, yielding a stream of material benefits (as is the case, for example, with information about a manufacturing process or the design for a new product).[9] It is less frequently a pure consumption good: even a new harmony is an input in the production of new musical ideas, or a new design in dress the basis for further innovations in design. It will not matter here whether we think that certain kinds of knowledge possess intrinsic worth in the Aristotelian sense, or whether we value knowledge in terms of its (potential) utilitarian applications.

3. On Designing Institutions for the Production of Knowledge

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[6] The theory of public goods has been much studied in the economics literature. Stiglitz (1988) contains a clear account.

[7] The real resource cost of transmitting, absorbing, and evaluating all the relevant information required to apply a production technology in a new setting has been found by economic studies to be an appreciable part of the total costs of projects involving the transfer of technology (see Teece, 1976).

[8] Recall Marx's observation: "Once discovered, the law of the deviation of the magnetic needle in the field of an electric current, or the law of the magnetization of iron, around which an electric current circulates, costs never a penny," (Marx, 1970, Vol. 1, Ch. XXV: 386).

[9] We do not mean to suggest by this that engineers and technologists have no aesthetics of their own.

Given this background, we seek to identify resource allocation mechanisms, more generally, socio-economic institutions, that can be relied upon in principle to produce knowledge in an efficient manner. The qualification bears emphasis. We are interested at this point in a thought-experiment: we assume that it is possible costlessly to design socio-economic institutions, with their attendant sets of rights, rules, and norms. We are interested in designing resource allocation mechanisms that can sustain an efficient production and allocation of knowledge of all kinds. By a resource allocation mechanism we mean, roughly speaking, a socio-economic institution. To set the ground for the thesis we will be arguing, it will prove useful to begin by implicitly considering a set of extreme (and unrealistic) circumstances in which there are several resource allocation mechanisms that are equally efficient as regards the production of knowledge. In these situations, it is a matter of social indifference which institution is established. But in the world as we know it, matters are different. So in Sections 5 and 6 we will probe more deeply into the characteristics of knowledge as a commodity and argue that it is socially desirable to institute not one, but simultaneously more than one resource allocation mechanism in the "knowledge sector". We will even suggest that there may be social advantages in encouraging these institutions in part to assume adversarial roles, and we will show that Science and Technology in fact assume these positions.

Of all possible resource allocation mechanisms, the one that has been most studied in economics is the market mechanism. As is now well known, if the market mechanism is not aided by further social contrivances, such as, for example, intellectual property rights, it can be relied upon not to sustain an efficient production of knowledge. More generally, the market mechanism has a tendency to discourage the production of public goods because of an inability on the part of producers to appropriate fully the value of the fruits of their activity.[10] Three schemes are available for overcoming the market's deficiency in this regard: two are by circumventing it altogether, and one is by aiding it. We elaborate upon them in turn.

(1) The first scheme consists in the government engaging itself directly in the production of knowledge, allowing free use of it, and financing the production cost from general taxation. This was at the heart of Samuelson's analysis of the efficient production of public goods (Samuelson, 1954). Government research and development (R&D) laboratories that publicly disclose their findings, such as agricultural research establishments, are an

[10] This is the well-known "free rider" problem in the supply of public goods. The earliest writers on this were Knut Wicksell and Eric Lindahl. See Musgrave and Peacock (1958) for abridged versions of the Wicksell-Lindahl analyses. Modern statements of the allocation problem associated with public goods are in Samuelson (1954) and Arrow (1971). The basic economics of public goods can be found in any textbook on public finance. See e.g. Musgrave (1968) and Stiglitz (1988).

example of this. It is as well to note that, in this scheme the volume of public expenditure in the production of knowledge, and the allocation of expenditure for the production of different kinds of knowledge, are both public decisions: they are decisions made by government.

(2) A second possible scheme is for society to grant intellectual property rights to private producers for their discoveries, and permit them to charge (possibly differential) fees for their use by others. This creates private markets for knowledge. Patent and copyright protections are means of enforcing intellectual property rights, and we will discuss their strengths and weaknesses at greater length in Section 7. But it is as well to note here that, in this scheme the producer (or owner) of a piece of information should ideally set different prices for different buyers, because different buyers typically value the information differently. In economics, these variegated prices are called Lindahl prices, in honour of the person who provided the first articulation of this scheme (see Musgrave and Peacock, 1958).

One problem with such markets is that they are inevitably "thin" (each market is essentially a bilateral monopoly, that is, it consists of the seller and a single buyer), and, therefore not a propitious environment for the emergence of prices that will sustain an efficient allocation of resources (Arrow, 1971). Another problem with them arises from the fact that transactions in knowledge are shot through with leakage. The point is that, for an exchange to be conducted efficiently, both parties need to know the characteristics of the commodity being transacted. In our example, the potential buyer needs to know what the piece of information is <u>before</u> the transaction is concluded. But once the potential buyer gets to know the information, it is difficult for the seller (e.g. the patent holder) to prevent the prospective buyer from benefiting, if the contemplated transaction is <u>not</u> concluded. Arrow (1962) argued that this is a particular difficulty whenever the transaction involves the fruits of fundamental research, for the findings of such research have possible applications in wide varieties of fields, some of which are not known to the would-be seller. This feature of knowledge, that its value is often very difficult to quantify, will figure prominently in what follows. It means that the economic use-benefits of knowledge are often hard to appropriate privately, and therefore to market efficiently. This is so even when patent protection of knowledge gives the owner transferable legal rights to exclude others from using that knowledge.

Matters are easier in the case of narrowly restricted knowledge about new technical processes and practical devices. This partly explains why it is a commonplace today to see A paying B a license fee for using B's patent on the manufacture of a new product, or on a new process for manufacturing an old product.

These considerations tell us that despite their limitations, the institution of patents and copyrights (and, for that matter, the practice of secrecy among private individuals and agencies) provides a mechanism for appropriating profits from discoveries and inventions. In short, while knowledge can in principle be used jointly, joint use can be prevented by legal prohibitions, or through the practice of secrecy. This can be socially desirable, because even though monopoly in the use of knowledge is inefficient (it involves the underutilisation of knowledge), it can be offset by the fact that the lure of monopoly profits makes researchers undertake R&D activity today. Therein lies the value of instituting patent laws, and of allowing secrecy to be practised by discoverers.

(3) A third possible scheme is for society to encourage private production of knowledge by offering public subsidies for its production, and by relying upon general taxation to finance these subsidies. A critical feature of this arrangement is that producers are denied exclusive rights to the output of their R&D activity: once it is produced, the knowledge is made freely available to all who care to use it (Pigou, 1932; Baumol and Oates, 1975; Dasgupta and Heal, 1979). In albeit imperfect forms, this scheme characterises research activities in public entities, such as universities, where much of the knowledge that is produced is prohibited from being patented, and where salaries and promotions and equipment are paid out of public funds (the subsidies!). We will study this resource allocation mechanism further in Section 7, where we will also study the role assumed by a special form of intellectual property right, namely priority, which plays a significant role in making the scheme more effective than it would otherwise be. The late Michael Polanyi's proposal (Polanyi, 1943-44), that the patent system should be abolished and replaced by a system where inventors are rewarded out of public funds, and where all potential users have unrestricted access to inventions, in effect advocated this third scheme over the second one. Among other things, our analysis will show why, and in what way, this proposal is defective.

Now, it is an interesting fact that if (a) everyone, including the government, can observe, know, and verify the same set of events or things, and (b) contracts can be specified in as much detail as is desired by people, then the three institutions outlined above are identical in terms of allocative efficiency; in particular, all three institutions would sustain an efficient allocation of resources in the production, dissemination, and use of knowledge. So it is a matter of indifference which institution (or their combination) is established. Interesting questions arise only if either (a) or (b) is violated. We will discuss these questions below.

It will be noticed even from this cursory description, that the first and third resource allocation mechanisms in our above list are similar in one important respect: the output of research is publicly shared. In contrast, the second mechanism treats the output as a private good. To be sure, the second scheme differs from the other two also as regards the source of funds: private versus public. But we will argue below that differences in the sources of funds are not an illuminating way of distinguishing Science from Technology. Government laboratories engaged in military research are publicly funded, but the secrecy that is maintained over their findings makes them part of Technology. So we will amalgamate the first and third schemes into one on the grounds that their attitudes to the output of research are similar, and conceive a two-way classification of institutions that are involved in research and development. Particular attention will be given to differences in the motivations of researchers working in the two realms. Each institution is characterised by its own specific rules of conduct and methods of training, and each tries strenuously to inculcate among its members its own particular brand of personal goal.

4. On institutions for the transmission and dissemination of knowledge

The approach we are pursuing here also sheds light on the institutional mechanisms through which knowledge is transmitted among scholars and disseminated to the general public.

This said, it needs emphasis that the distinction between production, transmission, and diffusion of knowledge is blurred. As in most service industries, producers and customers often work together to make use of the knowledge that is produced: rewards for the discovery of a new piece of knowledge depend upon the mechanisms of disclosure of this very piece of knowledge. Thus, institutions for the creation of new knowledge often develop the rules of transmission. Science and Technology are institutions where knowledge is disseminated as a public good and as a private good, respectively.

Equally, institutions for the transmission and dissemination of knowledge can affect the pattern of future knowledge production. Consider, for example, convents in Europe in the Middle Ages, music schools in Northern India (Patel, 1995), and Ph.D programs in modern universities (Dasgupta and David, 1994). These are institutions where production and transmission of knowledge go hand in hand. One may think of a continuum of institutions, which range from pure production to pure diffusion mechanisms, with the most frequent and interesting cases lying in the middle.

Even though the creation and dissemination of knowledge are closely interrelated, there are two reasons why we should consider them separately. First, the technological, institutional and financial characteristics of the institutions that produce and disseminate knowledge depend on exogenous shocks and investments, which are very often external to these institutions, but which create feed-backs on the world of ideas as well as on social cohesion and segmentation. Secondly, despite their heterogeneous genesis and nature, the mechanisms for the dissemination of knowledge are characterised by important regularities and lend themselves to a common analysis.

We noted earlier that in some institutions knowledge is disseminated as a private, in others as a public good. A mathematical theorem can be used and developed by other mathematicians with no use-fee. A novel, or a script for a movie, on the other hand, is subject to private property rights, and so cannot be replicated free of charge or, at best, consent. In the previous section we suggested a rationale for the co-existence of these two property-rights regimes. The characteristics of the institutions for transmission add further insights.

We begin by noting that technologies for transmission and diffusion affect the cost of reproduction and, thereby, feasible property-rights to knowledge. To put it another way, technology may affects the ability to protect or disclose ideas effectively. The possibility of defining and enforcing property rights is clearly dependent on technology.

Innovations like printing, recording (vinyl recording, tape recording, compact disks, and videos), radio, TV, and computers and the Internet have reduced the cost of diffusion of knowledge significantly. So they have reduced the possibilities with which knowledge can be appropriated. On the other hand, reproducibility makes copyright essential and, because it creates records, makes copyright relatively easy to enforce. This implies that the rents from a reproducible piece of knowledge are generated by diffusion to wider and wider audiences.

Vehicles for the diffusion of knowledge were, however, almost invariably created for other purposes. Consider, for example, commercial routes in ancient times (such as the Silk Way between Europe and China), or the Internet, as it has evolved in the last ten years. These were and are networks created for their own purposes (from trade to the creation of an invulnerable military system of communication) and sustained through their own financial returns. It was only subsequently that they became important channels for the transmission of knowledge among scholars and for its percolation to the outside world. Indeed, the transmission of knowledge, when it is treated as a public good, has to rely on subsidies, either provided directly (through public provision or incentives) or indirectly through cross subsidies from other markets and activities.

This blend of purposes influences the type of knowledge which is transmitted. The Silk Way provides a very useful example. Joseph Needham, in his monumental work on science and civilisation in China, has shown that while Chinese technologies travelled and diffused to the West, Chinese science had almost no influence in Europe:

> "... Chinese science, before the coming of the Jesuits, in spite of opportunities of intellectual intercourse much greater than has often been pictured, had very little in

common with that of the West.... But Chinese technological inventions poured into Europe in a continuous stream during the first thirteen centuries of the Christian era."[11]

Merchants, who were the vehicles for knowledge diffusion, had to bring back inventions of immediate practical use rather than abstract ideas and paradigms.

Consider, also, modern media for the widespread dissemination of arts, such as the compact disc and television. Here too, media which were created for the pure distribution of a given product, not only influenced the mode of creating knowledge, but also filtered the kind of output that is transmitted to the general public. Similarly, television, which in the post war period has been crucial in creating a common knowledge basis (and even a common language basis and culture) in many countries, was also responsible for creating a special style of information, and has filtered the kind of knowledge that is disseminated to the general public.

There are many reasons why channels of transmission mould or select the types of knowledge that are diffused. Language barriers, "rejection of the strange", and "complexity" are important factors. Returning to the Silk Way, whereas techniques were probably easily replicable and based on knowledge which was common both to the East and to the West, science and abstract speculations, instead, were based on concepts and on patterns of thinking, and were often so rigid, that scholars were unable to recognise and accept new elements from outside.

"... the Chinese had been observing and registering sun-spots since the first century, but even if any hint of this had reached medieval Europe, imitation or extension of the observations would not have been feasible, since in European ideas the sun was a perfect body and by definition could not have spots.[12]

In short, the diffusion of knowledge depends on the relative payoffs of knowledge transmission and learning. The cost of abandoning a set of pre-existing and well-established concepts may be too high (in terms of learning-time, status, and rents), even when the superiority of the new piece of knowledge is evident. Cost of learning and complexity depend on both the type of knowledge (understanding a new theorem requires complex skills) and the vehicle of transmission (you cannot use Internet if you have no computing skills).

5. Disclosure and Secrecy: Property Rights and Externalities[13]

[11] Needham (1954), Vol.I, section 7: 239 (1975 reprint).

[12]. Needham, 1954, Vol.I, section 7, p 239 (1975 reprint)

[13] This section is based on Dasgupta and David (1987).

These observations suggest that it is as social constructs that Science and Technology differ most profoundly. Both Science and Technology are collective organisations, or communities, with particular rules that are observed by those who wish to be recognised as participating members. Among communities of researchers who identify themselves as following scientific methods, some of these rules have to do with acceptable procedures for the statement and testing of theories, and for the form in which predictions are cast. These matters have been much discussed by philosophers and sociologists of science and we will not elaborate upon them here. Instead, we want to emphasise a crucial additional feature of the ethos of science, which is that scientists have an obligation to disclose all new discoveries and submit them for critical inspection by other members of the community. In other words the community rules instruct scientists to regard their (final) discoveries as collective, or public, goods regardless of the identity of the discoverer.[14] Thus, in submitting their finding to their peer group scientists, qua scientists, surrender claim to exclusion control of that information. In fact, the social norm is even more exacting: complete disclosure is the rule.

Thus, scientists hasten to publicise their findings, whereas technologists display reticence and on occasion downright secrecy; "scientists only write, engineers only read" gives an exaggerated aphoristic expression to this perceptive generalisation. We may then tentatively draw a sharp distinction between science and technology in regard to the disposition of their respective research findings and formulate it as a social imperative: if one joins the science community, one's (final) discoveries must be disclosed completely and speedily, whereas if one joins the technology community, such findings must not be fully revealed (immediately or eventually) to society at large, and possible not to one's fellow-technologists.

Granted that this is a caricature, but a good analytical distinction surely can afford to be somewhat overdrawn. Its defect is not that it is a caricature, but rather that, in delineating these behavioural norms, it describes without explaining. So, we should be asking why scientists and technologists show such different attitudes towards the disposition of their findings.

The answer may be seen to reside in differences in the goals of the institutions to which scientists and technologists belong. And the only consistent economic rationalisation of the phenomena of disclosure and secrecy is that Science aims at increasing the stock of knowledge by encouraging originality, whereas Technology seeks the rents that can be earned from this knowledge. To state it uncompromisingly, if somewhat metaphorically, Science views

[14] Mulkay (1977: 118) discusses the conflicts among scientists over voluntary limitations on informal (pre-publication) communication, which are created by the norm of full disclosure and the competition for priority.

knowledge as a public consumption good, while Technology treats it as a private capital good.[15] Thus, even though they compete for research talent, the two institutions are not directly in competition: their goals are different. Since their goals differ, neither institution provides a direct incentive for the other to perform well. Instead, competition is engendered within each institution by the simple expedient of encouraging the formation of rival research teams.

6. Why Two Institutions?

Why should society maintain two institutions with dissonant objectives if they are both involved in the production of what is essentially the same object, namely knowledge? One answer resembles the reason why juries are better able to decide when evidence is gathered by teams placed in adversarial positions. It is a deep and enduring fact that knowledge is difficult to quantify. It is at least equally hard for "society" to impute relative weights to the values of different kinds of knowledge. Moreover, there is often great uncertainty about the relative fruitfulness of different research strategies. A single institution, wedded to a single objective, would be biased in its support of certain kinds of research programmes, and thereby, to the production of certain kinds of knowledge. For example, Dasgupta and Maskin (1987) have shown that research teams competing within any given institution (whether Science or Technology) tend to choose projects that are not as diverse in their themes as would ideally be socially desirable. Sustaining two institutions with separate objectives permits society to enjoy a more diverse portfolio of projects, and thereby to span a wider range of potential research outcomes.

The second answer is based on the theory of agency. We could think of citizens and researchers as being engaged in a multi-principal/multi-agent relationship. The simplest case to analyse is one where there is a single principal and a single agent; so we will consider this case. Assume that the principal cannot observe the agent's effort. The problem is that the quality of research output depends not only on the agent's efforts, but also on pure luck. This is a problem for both parties, because the principal cannot say on the basis of observing an agent's output whether the agent was lazy but lucky, or whether he had worked hard but had been unlucky. Suppose now that the principal is risk-neutral and the agent is risk-averse. It is then

[15] By this we do not mean Science is not interested in applications; nor that it is interested solely in knowledge for the sake of knowledge. Scientists regularly investigate phenomena with a view to applications. But Science insists on the publicness (indeed, universal publicness) of knowledge, and is ultimately concerned with knowledge and its applications as consumption goods.

well known that if either the research venture is very risky or the agent is very risk-averse, the efficient contract resembles a fixed fee, whereas if neither holds, then the efficient contract involves awarding almost all of the value of the product to the agent. The former type of contract resembles the kind on offer in the institution of Science, as we have defined it above, the latter resembles those on offer in the realm of Technology.

The third answer is traditional. It has to do with appropriability. Some types of knowledge are inherently less easy to appropriate than others. The institution of Science, with its rule of disclosure, is consistent with private incentives if appropriation of the findings of research is technically difficult. If it is easy, then merely urging a person to disclose will not help. The institution of Technology is the natural habitat for the production of such types of knowledge.

Given the objectives in the institution of Science, the benefits to the scientific community from disclosure are two-fold. First, we may note that the existing pool of knowledge is a crucial input in the production of further knowledge. (As we have already mentioned, among other inputs are the ability and zeal of the investigator!) Disclosure increases the expected span of application in the search for new knowledge. To put it in other words, disclosure raises the social value of new discoveries and inventions by lowering the chance that they will reside with persons and groups who lack the resources (or abilities) to exploit them. Secondly, disclosure enables peer groups to screen and evaluate the new finding. The result is a new finding containing a smaller margin of error. The social value to the community of scientists is that scientific users of new discoveries can tolerate a higher degree of risk arising from other sources of incomplete information.

Contrast this with the situation in Technology. If each unit is concerned with the private rents (or profits) that can be earned from new discoveries (or new uses of old discoveries -- it comes to the same thing), secrecy is precisely what would be practised. It would not matter so much that the discovery has not been screened by rival units. What matters more is that it proves useful in yielding a privately capturable rent. Disclosure would reduce the private profits to the discoverer, because there would then be many people with whom profits would have to be shared.

But a piece of knowledge can be used simultaneously by any number of people, any number of times. Technically speaking, it is a durable good; and, as we noted earlier, there need be no rivalry over its possession. Once it is produced, knowledge ought, therefore, to be freely available to all (assuming, of course, that transmission costs are negligible). Thus, what we are identifying as the common purpose of Science is consonant with society's aims. Disclosure, in particular, is a necessary condition for the efficient use of knowledge. This rationalises the fact that so much science has throughout history been supported by public institutions and centres of learning, such as universities. Secrecy and the efficient use of knowledge are inimicable.

(We add parenthetically, that the monastic tradition in the West contributed greatly to the methodology of the new science of the seventeenth century. One important feature was the tradition of reproducing ancient texts, and checking their accuracy. This established an open transfer of knowledge, inasmuch as the content of both ancient and Arabic manuscripts were the sources of such theoretical science as the medieval world inherited. We would argue that financial support of the Church was one important historical condition favouring the development of the rule of disclosure in Europe. In contrast, the philosophers and scribes of medieval India tended to be less generous in sharing their knowledge. Indeed, important systems of logic, such as the Nabyanayya, have for the most part died with the scholars. It should not be surprising that medieval Indian logicians should have been so reticent: they were, generally speaking, obliged to provide for their support by acquiring patrons from among the landed aristocracy, and by acquiring pupils. They were not supported by any Order. They were compelled to be technologists. This was in contrast to the Buddhist tradition.)

7. Incentive Schemes

Earlier, we offered a two-way classification of possible resource allocation mechanisms for the production and dissemination of knowledge. They are Science and Technology. Technology is, roughly speaking, the market mechanism for knowledge. It is supported by the norms of secrecy and the rules of patents and copyrights. Science in contrast is a vociferously non-market resource allocation mechanism.[16] It is supported by the norm of disclosure and the rule of priority. The accompanying figure provides a schemata for Science and Technology.

7.1 Priority

The drawback with disclosure, as we noted earlier, is that in general it dilutes private incentives to produce knowledge. As we have also noted, society at large seeks to solve this

[16] This may explain why for the most part Science has been studied by sociologists and intellectual historians, and Technology by economists. Zimon (1981) suggests (wrongly) that scientific knowledge cannot be "an economic category", and so, not a proper subject for the application of economic analysis. It is a mistake to think that economics is exclusively concerned with the study of formal market processes. Non-market mechanisms fall equally within its disciplinary domain. This is because even they are involved in the allocation of resources.

problem by allocating funds for Science through public bodies. But what is the guarantee that scientists will not slack? The institution of Science addresses this problem by nurturing the rule of priority as a method of rewarding researchers. We will elaborate upon the rule of priority below. But it is as well to note here that the rule provides an incentive for disclosure. By this we do not, of course, mean that scientists disclose everything they find, the moment they find them. There are interesting strategic elements in a scientist's decision of what and when to disclose. A scientist is loath to disclose partial results for fear that rivals will otherwise reap the more important results. But this merely points to the larger truth, that the rule of priority elicits disclosure. And somewhere between full disclosure and secrecy lies another social contrivance, the system of patents and copyrights, which Technology often relies upon.

The rule of priority - the central method of rewarding scientists for their discoveries - serves two purposes at once. First, it establishes a contest, a race, for scientific discoveries. Since a scientist's effort cannot in general be monitored publicly, reward cannot be based upon it. For if it were, a scientist would have an incentive to slack and claim that he has worked hard (this is the agency problem we alluded to earlier). There would be no way to refute his claim. Nor can his intention be the basis for reward. Intention cannot be monitored publicly either. So reward cannot be based on intention. This is one reason, among others, why a scientist is not admired for failure, no matter how difficult is the problem upon which he has been engaged. He receives sympathy, perhaps, but not admiration. By contrast, success, if disclosed, can be monitored and vetted publicly. So reward can be based upon it; the greater the achievement, the larger the reward in the form of salary increases, subsequent research grants, scientific prizes, eponymy and most generally, peer-group esteem.

A method of payment alternative to one based on priority would be a fixed fee for entering a scientific race. But this would dull the incentive to work hard, since scientists would collect the fee irrespective of whether they produce anything of interest. So the reward must be made to depend in some way on achievement. However, it is often difficult to determine how far behind the winner the losers of a scientific race are when the winner announces his discovery.[17] (Those who were left behind could copy the winner's results and claim that they had arrived at them independently.) For this reason, it is not possible to award prizes on rank. Thus, unlike tennis tournaments, science does not usually pay the "runners-up". This suggests a type of

[17] But not always. Word gets around, even of half-finished work, provided the runners-up have sufficiently well-established track-records. Then of course, eventual losers publish progress reports along the way. Writing about the race for the discovery of the structure of DNA, Medawar (1968) says: "If Watson and Crick had not made it, someone else would certainly have done so - almost certainly Linus Pauling, and almost certainly very soon. It would have been the same discovery too; nothing else could take its place". (Medawar [1982], p. 272)

reward system which is compatible with individual incentives, one where, roughly speaking, the winner is awarded all that is to be dispersed by the community. A reward system based upon priority mimics this.

But taken alone, the rule of priority would place all the risks involved in the production of scientific knowledge firmly on the shoulders of scientists. This cannot be efficient if scientists, like lesser mortals, are risk-averse. And one would expect individuals without private means to be particularly averse to shouldering all the risk. How would they support themselves if they were not successful in the races they chose to enter? It would not do to argue that they could finance themselves by borrowing in the credit market from institutions that were risk-neutral, thereby shifting risk to those institutions in an efficient manner: there would be no guarantee that the borrowers will not slack, increase the chance of their losing the race and thus raise the probability of default on their loans. In short, the credit market also suffers from moral hazard.

We conclude then that scientists need to be paid something regardless of the extent of their success in the R & D races they choose to enter. It is in this light that a remark of Arrow's [1962], "...the complementarity between teaching and research is, from the point of view of the economy, something of a lucky accident", assumes its full significance. Roughly speaking, a modern scientist's reward comes in the form of a fixed wage (for teaching, should he be engaged in academia) and bonuses (promotions, scientific awards and general recognition) for priority in discoveries and inventions.

The second purpose the rule of priority serves is in eliciting public disclosure of new findings. Priority creates a privately-owned asset - a form of intellectual property - form the very act of relinquishing exclusive possession of the new knowledge. It is a remarkable social innovation. In science priority is the prize; it conveys "moral possession" (Medawar [1982]) to the discoverer when legal possession is not possible and, what is more pertinent, where it is not desired by any party.

Robert Merton, who has done so much to increase our understanding of the sociology of science, has explained the often-puzzling importance that scientific communities attach to resolving priority disputes among contestants, in the following functional terms:

"...scientific knowledge is not the richer or the poorer for having credit given where credit is due: it is the social institution of science and individual men of science that would suffer from repeated failures to allocate credit justly." (Merton [1973], p. 307). But Merton's explanation leaves it unclear in what way the institution of science would suffer.

The explanation we are advancing here is based on the nature of efficient contracts in a situation where the individual scientist, as an individual, has different aspirations from those of the institution (Science) to which he belongs; and where different agencies within the organisation - viz. the scientists himself and his peer group - cannot jointly observe everything of interest, such as a scientist's research efforts.

Differences in aspirations (or goals) exist between the scientist and society because, among other things, society at large and the community of scientists collectively do not care who makes a discovery, given that the discovery is made. But for the individual scientist, the identity of the discoverer matters very much: each wants to be a discoverer. The priority rule provides the basis on which efficient incentive contracts can implicitly be entered into (tenure for creative work, prizes for outstanding discoveries, and so forth). It is then surely to be expected that scientists, as individuals and as members of collective bodies, will devote a great deal of attention to the resolution of priority disputes, should these occur. The rules by which priority is awarded, and the procedures that are followed in implementing them, form a vital element in making the reward-structure in which the individual scientist operates more dependable, that is, more predictable.

Once a scientific discovery is made, announced, and disclosed fully for confirmation by means of replication, the new information become unmarketable. It is in this sense that the practice of science, in contrast to the practice of technology, is not a market-oriented activity. Precisely because it is a non-market institution, science has had to rely heavily for its self-preservation and reproduction upon elaborate rituals and codes of behaviour, norms which are instilled into its members through the education process. Here again, the complementarity between teaching and research has been a boon for the institutionalisation of open science. Since neither the discoverer, nor the institution of science, can earn financial profits from discoveries, reward for priority in discovery perforce contains a strong non-pecuniary element. Love of the "scientific lifestyle", commitment to "academic freedom", a craving for recognition, if not fame, among one's peer-group, disdain of "lucre" as a motivation for one's work, are implicitly imparted to students in the course of their education and research apprenticeship. It is this delicately fashioned social ethos which binds individuals into communities of scientists and creates a counterpoise to the blandishments offered by Technology.

7.2 Patents, Copyrights, and Secrecy

Compare the form of the reward system in Science with the one found in Technology, which are linked to the often-privately appropriated profits from knowledge. The beneficiary of such additions to knowledge is presumably willing to pay for them. This creates the possibility of a reward structure that is not closely linked to priority in original discoveries. A commercially successful application of a long-accepted scientific principle typically will award the adapters and adopters of the theory, not its originator(s), even when the former may have contributed nothing more than a restatement of the principle in terms that have exposed its commercial relevance.

Secrecy provides a means of capturing profits from new findings. But secrecy is not completely reliable; it can even be less reliable than public disclosure in its consequences for the individual possessing the knowledge. Apart from anything else, there may be little to prevent rivals from making the same discovery at a later date and sharing the profit. The institution of patent protection attempts to remedy this. Patent systems in principle allow individuals and firms to disclose their findings without fully diluting the profits they can earn. The system in effect offers a private reward for disclosure and makes the award on the basis of priority of disclosure. The reward itself is tied to the private profits that can be earned. By connecting disclosure with the right to exclusive use of discoveries, the patent system undertakes to solve the problem of financing the pursuit of scientific, that is, publicly disclosed, knowledge.

The patent system is both interesting and problematic because it represents a conjunction of the distinctive and antithetical mores of Science and Technology in regard to their goals, and thus to their treatment of newly produced knowledge. Looking backwards it rewards additions to knowledge that are divulged, and does so on the basis of priority. But to finance the award it looks ahead to a contrived limitation of access to the new knowledge. As a social invention, it incorporates a fundamental feature of the reward structure of the scientific community, which seeks to create intellectual property rights in what are (naturally) durable, jointly-usable goods. However, by leaving the determination of the economic value of the property to the workings of the market, the assignment of patents rights necessarily inhibits the utilisation of that property. We noted this point earlier.

One should note, however, that a complete monopoly over the use of knowledge cannot be guaranteed by an arrangement that is designed to elicit some disclosure of information, as it is in the case of patents. From the standpoint of the patent-holder the arrangement is defective, because disclosure often allows rivals to search for alternative products, or alternative processes to manufacture the same product. At some level this failing of the patent system is unavoidable, since mere disclosure that a problem has been solved, may prove in itself to be valuable to rival problem-solvers; the latter then channel resources in directions that increase the likelihood that a substitute solution (or worse still, a superior solution) will be found. For example, it has been suggested that research on semiconductors was sufficiently far advanced in many places by the close of 1947 that "from the knowledge that such a thing as a transistor was possible, there were perhaps twenty-five organisations which could have made one" (Braun and MacDonald [1982], p. 46). The Bell Laboratories group, which discovered the point contract transistor in late December of the year, therefore faced a conflict between its perceived need to better understand the transistor for the purposes of filing patent applications, and the interests of the inventors (John Bardeen and William Brattain) in establishing their scientific priority by publishing a paper in the Physical Review. Although the first patent application was filed in February 1948, the discovery was kept a close secret within Bell Laboratories for some seven months, up to the eve of the publication of the Bardeen-Brattain paper.

There is, however, another side to this coin; as there almost always is. The patent system permits inventors to advertise in a more credible way their claims about possessing useful knowledge, while at the same time not divulging this knowledge completely to others. It is a commonplace that research experience leading to a patentable invention generates tacit technical knowledge not contained in the patent application itself, but complementary to it. When such necessary knowledge can be communicated easily, the purpose of filing the patent may be primarily to signal the availability of a trade secret for sale.

8. On endogenous institutions and public policy

We have investigated institutions for the creation and transmission of knowledge as efficient resource allocation mechanisms. We have also argued that the market cannot be relied upon to sustain an efficient production of knowledge and that public policy is important either to circumvent or to aid the funcioning of the market. By looking at Science and Technology we have developed a two way clasification of possible resource allocation mechanisms. Science, is a non market allocation mechanism, where knowledge is treated as a pure public good and where the rule of priority provides an incentive scheme for disclosure. Technology, is a market allocation mechanism, where knowledge is treated as a private good and where patents and copyrights preserve property rights. The central point we are trying to raise is that the distinction between the two entities should be based neither on the type of knowledge they produce nor on the methods of inqury they adopt. Rather, they differ in the institutional arrangements involving the allocation of resources for enquiry.

Yet institutions emerge and evolve endogenously. They change according to the type of knowledge they rule, the interests they serve and the returns they generate. Given the public good nature of knowledge, this process has inherent market failures and it is not necessarily optimal in terms of social welfare. There are many cases reported, where institutions have been negatively affected by vested interests both related to knowledge itself, or related more generally to the regulation of society.

Exclusive control over a given body of knowledge and vehicles for transmission creates rents for insiders. This can happen in many different ways. Peer groups devise languages and codes which speed up internal interaction. But codes raise entry costs and keep outsiders at bay. No one can become a peer without learning the code. The code can strictly be a language, a technique or a set of specific notions. Preserving that very set of notions as the dominant one also preserves the rents of the insiders, but does not necessarily favours the creation of new, useful knowledge. Examples abound. We have discussed above the inability of superior Chinese scientific findings to diffuse in Medieval Europe because they were inconsitent with the established body of scientific notions. Or, think at the role of art academies in teaching and defining one style and therefore preventing stylistic innovation.

Inaccessibility of knowledge could be due to secrecy or simply technological complexities. The technology of different media may have a tremendous impact on society, in terms of cohesion and segmentation, strictly related to learning patterns. Initial diffusion of the press increased social cohesion among those who were able to read but also strengthened social exclusion of the illiterates. Only later, with growing litteracy, the press became a vehicle for global diffusion. The same thing is happening for the Internet. In the short run, computer technology appears to widen the gap among "ins" and "outs", as well as generations,with repercussions on the segmentation of the labor market.

At the opposite level, when knowledge is easily reproducible, the inability to define and enforce effciently intellectual property rights may well jeopardise private incentives to invest in knowledge creation. We have discussed at length the functioning of property rights as incentive schemes. An interesting example of how copyright law completely changed the incentive to innovate is provided by Henderson, Jaffe and Trejtenberg (1996). They show that university patenting increased and research spending almost tripled between 1965 and 1988. A probably central cause for this development, was a 1980 change in the patenting federal law, the Bayh-Dole act. The new law allowed universities to patent the results of publicly funded research. The old legislation (which was aimed at preserving the public good nature of the new knowledge created with public funds) hampered any incentive to develop basic research into commercial applications. Another example, reported by Baumol, is given by North and Thomas in their account of the invention of the ship's chronometer to determine longitude in the eighteenth century. The incentive for this invention was a large governmental prize and not the prospect of commercial profits, probably because there was no effective patent protection[18].

Understanding the mechanics of institutions is extremly important when we move to policy design. This is now well established in regulation, but perhaps less so for science, technology and education policies. In other words, policies should be designed as tools to improve the working of institutions which have their own endogenous dynamics.

The problem, though, is that the lack or malfunctionig of institutions that effectively promote creation and diffusion of knowledge must sometimes be addressed at the broader level of the overall values of society. In other words, payoffs from the creation and diffusion of knowledge (and thus the threshold between private and public good) also depend on the overall sets of values of the society. William Baumol's analysis of the allocation of entrepreneurship between productive and unproductive activities applies very well here. Baumol argues that such an allocation is influenced by the relative payoffs society offers to such activities. To discuss the unfavourable reward system of Ancient Rome, among other evidence, he reports a beautiful anedoct drawn from Finley:

> '(..) a man invented unbreakable glass and demonstrated it to Tiberius in anticipation of a great reward. The emperor asked the inventor whether anyone shared his secret and he was assured that there was no one else; whereupon his head was promptly removed, lest, said Tiberius, gold be reduced to the value of mud'[19]

We do not want to push the story of Tiberius and the unbreakable glass any further, as we would move to the realm of the political economy of institutional design, which is well beyond the scope of this chapter. Yet, once we acknowledge that institutions have an endogenous dynamics, we must make sure that we understand where their roots lie.

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[18] Baumol, 1990, p.900, footnote 4, reported from North and Thomas, 1973

[19]. Baumol, 1990, p. 900 reported from Finley, 1985, p. 147

References

Arrow, K.J. (1962) "Economic Welfare and the Allocation of Resources for Inventions" in R.R. Nelson (ed.), *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Princeton University Press.

Arrow, K.J. (1963) "Uncertainty and the Welfare Economics of Medical Care", *American Economic Review* 53: 941-73.

Arrow, K.J. (1971) "Political and Economic Evaluation of Social Effects and Externalities" in M.Intrigator (ed.), *Frontiers of Qualitative Economics*, (Contributions to Economic Analysis vol. 71, Amsterdam: North-Holland Publishing Co.)

Barzel, Y. (1968) "Optimal Timing of Innovations", *Review of Economics and Statistics* 50.

Bhattacharya, S.. and J.R. Ritter (1983) "Innovation and Communication: Signalling with Partial Disclosure", *Review of Economic Studies* 50.

Baumol, W.J. and W.E. Oats (1975) *The Theory of Environmental Policy: Externalities, Public Outlays, and the Quality of Life*, Englewood Cliffs, N.J.: Prentice-Hall.

Baumol, William, J., (1990), 'Entrepreneurship: Productive, Unproductive and Distructive', *Journal of Political Economy*, vol. 98, pp. 893-921

Bell, E.T. (1937) *Men of Mathematics*, New York: Simon and Schuster.

Boorstin, D.J. (1984) *The Discoverers: A History of Man's Search to know his World and Himself*, Random House (New York).

Boyer, C.B. (1985) *A History of Mathematics*, Princeton, N.J.: Princeton University Press.

Braun, E. and S. MacDonald (1978) *Revolution in Miniature: The history and impact of semiconductor electronics*, Cambridge: Cambridge University Press.

Brooks, H. (1967) "Applied Research: Definitions, Concepts, Themes" in U.S. Congress, House Committee on Science and Astronautics, Subcommittee on Science, Research and Development, *Applied Science and Technological Progress*. Washington, D.C.: GPO.

Butterfield, H. (1957) *The Origins of Modern Science*, Second Edition, London: Bell and Hyman.

Coolidge, J.L. (1949) *The Mathematics of Great Amateurs*, Oxford: The Clarendon Press.

Dasgupta, P.S. and P.A. David (1987), "Information Disclosure and the Economics of Science and Technology", Ch. 16 in G.R. Feiwel, ed., *Arrow and the Accent of Modern Economics Theory*, New York: New York University Press.

Dasgupta, P.S. and Heal (1979) *Economic Theory and Exhaustible Resources*, Cambridge: James Nisbet and Cambridge University Press.

Dasgupta, P.S. and E. Maskin (1987) "The Simple Economics of Research Portfolios", *Economic Journal* 97: 581-95.

Dasgupta, P.S. and J. Stiglitz (1980) "Uncertainty, Industrial Structure and the Speed of R and D", *Bell Journal of Economics*, 11: 1-28.

David, P.A. "The Economics of Patronage and the Historical Roots of the Institutions of Open Science", HTIP Working Papers Series (Center for Economic Policy Research, Stanford University), January.

David, P.A., D.C. Mowery, and W.E. Steinmueller, (1987) "The Economic Analysis of Payoffs from basic Research - An Examination of the case of Particle Physics Research" (A Report to the Office of Energy Research, U.S. Department of Energy). Canter for Economic Policy Research, high Technology Impact Program, Stanford University, December.

Feingold, M. (1984), *The Mathematicians' Apprenticeships: Science, universities and Society in England, 1560-1640*. Cambridge University Press.

Finley, M.I. (1965) "Technical Innovation and Economic Progresses in the Ancient World", *Economic History Review* 2nd Ser., vol 18(1), August: pp. 29-45.

Finley, Moses, I., (1985) '*The Ancient Economy'*, 2nd ed. London, Hogarth

Henderson, R., A. Jaffe and M.Trejtenberg, (1995), 'Universities as a Source of Commercial Technology: A Detailed Analysis of University Patenting', NBER Working Papers 5068, March 1995

Hirsh, F. (1976) *Social Limits to Growth*, Cambridge, MA: Harvard University Press.

Hirshleifer, J. (1971) "The Private and Social Value of Information and the Reward to inventive Activity", *American Economic Review*, 61(4), September: pp. 561-74.

Holstrom, B. (1982) "Moral Hazard in Terms", *Bell Journal of Economics*.

Klein, B.H. (1962) "The Decision Making Problems in Development" in R.R. Nelson (ed.), *The Rate and Direction of Inventive Activity: Economic and Social Factors,* Princeton University Press.

Kline, M. (1953) *Mathematics in Western Culture*, new York: Oxford University.

Kuhn, T. (1970) *The Structure of Scientific Revolutions*, Chicago: University of Chicago Press, Second Edition.

Kuhn, T. (1977) *The Essential Tension*, University of Chicago Press.

Lazear, E. and S. Rosen (1981) "Rank Order Tournaments as Optimum Labour Contracts", *Journal of Political Economic* 89(5), October: pp. 841-64.

Leff, G. (1968) *Paris and Oxford Universities in the Thirteenth and Fourteenth Centuries: An Institutional and Intellectual History*, New York: John Wiley and Sons.

Lind, R. (ed.) (1982) *Discounting for time and Risk in Energy Policy,* John Hopkins University Press (Baltimore).

Marx, K. (1970) *Capital* (English translation, Moore and Aveling), London: Lawrence and Wishart.

Mathais, P. (1979) *The Transformation of England*, New York: Columbia University Press.

Medawar, S. (1982) *Pluto's Republic*, Oxford University Press.

Merton, R.K. (1938) "Science, Technology and Society in Seventeenth century England", *Osiris* vol IV.

Merton, R.K. (1973) *The Sociology of Science: Theoretical and Empirical Investigation,* edited by N.W. Storer, University of Chicago Press.

Mookerjee, D. (1983) "Optimal Incentive Schemes with Many Agents", *Review of Economic Studies* 50.

Mowery, D.C. (1983) "Economic Theory and Government Technology Policy", *Policy Sciences* vol 16, pp. 27-42.

Mulkay, J.J. (1972) *The Social Process of Innovation: A study in the Sociology of Science*, London: MacMillan.

Mulkay, J.J. (1977) "Sociology of the Scientific Research Community", Ch. 4 in I. Spiegel-Rosing and D. de S. Price, (eds.) *Science, Technology and Society*, London: Sage.

Musgrave, R.A. (1968) *The Theory of Public Finance*, Second Edition, New York: McGraw-Hill.

Musgrave, R.A. and A.T. Peacock, eds. (1958) *Classics in the Theory of Public Finance,* London and New York: MacMillan.

Musson, A.E. (1972) ed. *Science, Technology and Economic Growth in the Eighteenth Century*, London: Methuen & Co.

Nalebuff, B. and J. Stiglitz (1983) "Prizes and Incentives: Towards a General Theory of Compensation and Competition", *Bell Journal of Economics*, Spring 14.

Needham, Joseph, (1954) '*Science and Civilisation in China'*, Cambridge, Cambridge University Press

Nelson, R. (1982) "The Role of Knowledge in R & D Efficiency", *Quarterly Journal of Economics* 97.

Nordhaus, W. (1969) *Invention, Growth, and Welfare*, Cambridge, Mass.: MIT Press.

North, Douglass C., and Thomas, Robert, Paul, (1973) '*The Rise of the Western World: A New Economic History'*, Cambridge, Cambridge University Press

Patel, A., 1996, 'Oral Transmission in Indian Classical Music: the Gharana System', Fondazione Eni Enrico Mattei, Note di Lavoro, 28.96

Pavitt, K. (1987) "The Objectives of Technology Policy", *Science and Public Policy* 14: 182-88.

Penrose, E. (1951), *The Economics of the International Patent System*, Baltimore: The Johns Hopkins Press.

Pigou, A.C. (1932) *The Economics of Welfare*, London: MacMillan Co.

Price, D. de S. (1967) "Research on Research" in *Journeys in Science: Small Steps - Great Strides*, D.L. Arm (ed.), Albuquerque: University of New Mexico Press.

Polanyi, M. (1943-44) "Patent Reform", *Review of Economic Studies* vol.11.

Ravetz, J.R. (1971) *Scientific Knowledge and its Social Problems,* Oxford: Clarendon Press.

Redondi, P. (1987), *Galileo: Heretic* (translated by R. Rosenthal from the 1983 Italian edition), Princeton N.J.: Princeton University Press.

Rothblatt, S. (1985) "The Notion of an Open Scientific Community in Historical Perspective", ch. 2 in M. Gibbons and B. Wittrock, eds. *Science as a Commodity: Threats to the Open Community of Scholars*, Harlow, Essex: Longmans.

Salomon, J.-J. (1973) *Science and Politics*, translated by Noel Lindsay, London: MacMillan Press.

Samuelson (1954) "The Pure Theory of Public Expenditure", *Review of Economics and Statistics*, vol. 36: pp. 387-89.

Teece, D. (1976) *The Multinational Corporation and the Resource Coast of International Technology Transfer*, Cambridge, MA: Ballinger.

Varian, H. (1985) *Microeconomic Analysis*, Second Edition, New York: W.W. North.

Vicenti, W.G. (1986) "The Davis Wing and the Problem of Airfoil Design: Uncertainty and Growth in Engineering Knowledge", *Technology and Culture* vol 27(4), October: pp. 717-58.

Westfall, R.S. (1985) "Galileo and the Jesuits", *Indiana University Distinguished Faculty Research Lecture*, Bloomington, Indiana.

Whitley, R. (1984) *The Intellectual and Social Organization of the Science,* Oxford: Clarendon Press .

Ziman, J. (1981) "Can Scientific Knowledge be an Economic Category?" in J. Ziman *Puzzles, Problems and Enigmas*, Cambridge: Cambridge University Press.