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Modelling science as a contribution good☆

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ABSTRACT

The non-rivalness of scientific knowledge has traditionally underpinned its status as a public good. In contrast we model science as a contribution game in which spillovers differentially benefit contributors over non-contributors. This turns the game of science from a prisoner's dilemma into a game of 'pure coordination', and from a 'public good' into a 'contribution good'. It redirects attention from the 'free riding' problem to the 'critical mass' problem. The 'contribution good' specification suggests several areas for further research in the new economics of science and provides a modified analytical framework for approaching public policy.

1. Introduction

1.1. Towards a new economics of science

In their landmark paper Dasgupta and David (1994) described as the 'old economics of science' the work of Nelson (1959) and Arrow (1962) in which the 'public good' characteristics of knowledge were seen as leading inevitably to 'market failure' and 'underinvestment' in science. Their objective was to develop a research agenda for a 'new economics of science' using contemporary advances in the economics of information, the theory of principal and agent, contract theory, the theory of property rights and the theory of games. Romer too (1990) has suggested that research does not have purely public good characteristics.

These new tools would help to explain the structure of prevailing institutions and to explore ways in which 'knowledge differs from other durable public goods, such as, for example, laws and constitutions, or lighthouses, for that matter' (p. 491). In particular Dasgupta and David contrast the social organisation of 'Science' with that of 'Technology'. The 'republic of science' with its relatively 'open' conventions with respect to disclosure and the sharing of new results is buttressed by incentive mechanisms that reward 'priority'. The world of technology with its more secretive and restrictive treatment of knowledge is buttressed by property rights (patents) and incentives derived from the pursuit of rents derived from innovation. Individual scientists in this conception might inhabit both worlds although the behavioural norms in each are very different. In a telling sentence Dasgupta and David (p.498) assert that 'modern societies need to have both communities firmly in place and attend to maintaining a synergistic equilibrium between them'.

1.2. The contribution good

This paper offers a model of science that incorporates both the worlds of exclusion and openness. It does so in a way that casts some new light on how these seemingly contradictory principles can co-exist and how institutions have evolved to harness them to social advantage. At the heart of our model there lies a simple set of propositions. Scientific knowledge indeed can be regarded as a common resource. The knowledge itself is non-rival. But unlike lighthouses which in the conventional story dispense their blessings on contributors and non-contributors alike, accumulated scientific knowledge is not automatically accessible by any passer-by or person of average curiosity. To understand scientific knowledge it is necessary to become a scientist (Rosenberg, 1990). Further (and more important for our model) even codified knowledge cannot be properly understood without access to the tacit knowledge that is a complementary product of scientific research Polanyi (1967). Dasgupta and David (pp. 493–495) recognise that the 'complementarity between the two forms of knowledge has important implications for the way research findings can be disseminated' and we concentrate on one such possible implication.

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If the possession of 'tacit knowledge' is a necessary condition for understanding a pool of codified papers and results; and if a necessary condition for accumulating tacit knowledge is the actual undertaking of scientific work and engaging with others in the republic of science; then the only people who are able to benefit directly from an accumulating pool of research results will be those who have in some degree contributed to it.

This 'tacit dimension' to scientific knowledge suggests two consequences. The costs of copying research and of commercialising it are significant, and these costs are higher for 'outsiders' than for 'insiders'. When Mansfield et al. (1981) examined 48 products that, during the 1970s, had been copied by companies in the chemicals, drugs, electronics and machinery industries of New England, they found that the costs of copying were, on average, 65 per cent of the costs of original invention, consuming on average 70 per cent of the time of original invention. Those costs and time frames reflect the fact that the copiers had to commit significant resources into (re)discovering for themselves the tacit knowledge embedded in the original discoveries and embedded in their commercialisation (which involves the creation of new production facilities, etc.) thus showing that the (re)discovery of tacit knowledge incurs very real costs.

Equally, in his study of spillovers of knowledge of the Transversely Excited Atmospheric (TEA) Pressure CO_2 Laser, Collins (1974, p. 176) suggested that the costs of copying solely from the literature could become effectively prohibitive because "To date, no-one to whom I have spoken has succeeded in building a TEA laser using written sources (including blueprints and internal reports) as the sole source of information". Personal visits to pre-existing TEA laboratories were an essential part of learning how to build them. But significant prior research in the field was needed before visiting for two reasons. First, because "it was only previous knowledge" that enabled visitors to benefit from what they had seen (Collins, 1974, p. 177) and second because "nearly every laboratory expressed a preference for giving information only to those who had something to give in return" (p. 181).

It is this requirement to accumulate tacit knowledge through a process of mutual engagement that to some extent explains the observed willingness of scientists to share knowledge even in the for profit sector. In a survey of 11 American steel companies, von Hippel (1988) found that 10 of them regularly swapped proprietary information with their rivals. In an international survey of 102 firms, Allen et al. (1983, p. 202) found that no fewer than 23 per cent of their important innovations came from swapping information with rivals – "Managers approached apparently competing firms in other countries directly and were provided with surprisingly free access to their technology". Commercial scientists share knowledge with each other because it is judged that isolation from the mutual learning engendered by the process of sharing will ultimately leave them at a disadvantage.

A pure contribution good we therefore define as a good whose benefits are non-rival over contributors but that cannot be accessed by non-contributors. The tacit dimension to scientific knowledge means that it will tend to exhibit these characteristics. Spillovers will favour contributors over non-contributors and self-interest will therefore produce a degree of 'openness'. We do not doubt that the nature of certain types of academic contract and the evolved conventions of universities and other research organisations also buttress 'openness'.[1] Our results, however, will depend not merely upon this 'openness' but on the additional fact that the beneficiaries are, either in the nature of things or as a result of additional supporting institutions, those scientists who have made a contribution.

Dasgupta and David (p. 502) invoke the theory of repeated games as one possible approach to the emergence of cooperative behaviour between groups of scientists even in the context of the 'prisoners' dilemma'. Our proposed treatment of science as a 'contribution good' leads to a rather different structure of the game and hence somewhat different incentives. We show that the archetypal framework for analysing science changes from the 'prisoner's dilemma' to a game of 'pure coordination' – with potentially very different implications for public policy.

Scientists in our model aim to maximise the rent that can be achieved from exploiting the common resource of science. They can only do this if they can also access the world of 'technology' with its legal protections to patent holders or other means to ensure payment from those ultimately benefiting from innovations. Thus, it is the willingness of people to pay for the (rival and excludable) products of innovation that ultimately drives the system and we consider a world in which there are means – either deriving from secrecy and other impediments to information flows or a robust framework of patent protection – of securing financial gain from innovation. There is no government or other funding specifically for 'pure science' (which is not to say that government demand for particular products deriving from the world of technology might not be important).[2]

1.3. Contribution goods and club goods

This paper considers a model of science where scientists must decide whether or not to make a contribution to knowledge that can be accessed by other contributing scientists. Contributing scientists form an implicit 'college' that might initially be formally and collectively constituted (a 'visible' college) but that might also in suitable conditions develop and grow spontaneously in response to purely private interests (an 'invisible' college).[3] A pure contribution good is non-rival over contributors but is not accessible by non-contributors. Where this asymmetry in the availability of external benefits is sustained not by formally designed and imposed organisational constraints but by the inherently tacit nature of much scientific knowledge, the situation in science takes on the same character as that which prevails in economic sectors characterised by Marshallian external economies, agglomeration economies and network externalities. Indeed Callon (1994, p. 411) specifically suggests that 'we need to abandon the notion of information and use that of network in its place'.[4] As the stock of scientific work increases, it confers benefits on all users and not just on the marginal contributor, just as a new firm might lower the costs of incumbents in an industry or new members of a social website might make it more useful to existing users. These circumstances can be interpreted as an impediment to the initial development of a sector, a powerful source (once established) of dynamic competitive advantage, and, in some circumstances, a reason to expect a socially suboptimal industry size and to recommend a public subsidy.

1 Dasgupta and David (1994, pp. 498–505) discuss the nature of these contracts. See also Lazear (1997) and Carmichael (1988).

2 Government purchases clearly affect the conduct of science – most obviously in the fields of defence, computer systems or the products of the medical equipment and pharmaceuticals industries.

3 The term 'invisible college' was first used by Price (1963). He used the term to describe the secret nature of the nascent Royal Society in the years before the Restoration as it avoided publicity and hid from a hostile Church. We use the concept 'invisible college' in a somewhat different context as a metaphor to reflect not secrecy but the spontaneous growth of cooperation between contributing scientists.

4 Callon emphasises many of the points that we rely upon in formulating the contribution good model. The fact that new ideas are often quite difficult to get across to others and that achieving a common understanding is a prerequisite for further advance are characteristics of science that are consistent with the approach of this paper.

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We use the word ‘college’ as the collective noun for a group of scientists. This has affinities with the concept of a ‘club’ analysed by Buchanan (1965) – essentially a means of supplying a good that is non-rival but excludable (with respect to non-contributors) at low cost. Buchanan (1965, p. 2) argues that his theory applies to situations ‘where the optimal sharing group is more than one person or family but smaller than an infinitely large number’. Science we argue is akin to a pure ‘social club’ in that the members themselves supply the ethos that makes the club attractive. Again, however, the analogy is not perfect because ‘exclusivity’ can be an important feature of social clubs and expansion can adversely affect the existing membership. In our model of science membership of the ‘college’ is not restricted and additional members always make a non-negative contribution to college resources.

In Sections 3–6 we set out a simple model of science as a contribution good. As a preliminary, Section 2 compares the traditional public good problem with the contribution good problem using the framework of a two-person contribution game. Science is not a two person game but the two person strategic form enables us to make clear the assumptions with respect to spillovers that we rely upon in the rest of the paper. Section 3 develops the contribution good model in the simplest setting of a population of scientists of equal ability while Section 4 investigates the properties of the model when scientists are of variable ability and identifies the equilibrium size of ‘college’ that will be formed (and the minimum size that is self-sustaining). The welfare implications of the model are briefly outlined in Section 5 and a special case in which scientists' abilities take on a uniform distribution is presented in Section 6. In Section 7 we relate the contribution good model of science to the historical development of scientific institutions and suggest some possible future lines of research.

2. The public good and contribution good models compared

The public good case is illustrated in the form of a collective action game represented by the entries in Table 1. There are two players. Each has to decide whether to contribute ($s_i = 1$) or not to contribute ($s_i = 0$) to the joint fund of science (S). This fund is the sum of the contributions of the players $S = \Sigma s_i$ ($i = 1, 2$). To contribute, each player incurs a private cost of $c > 0$. In the table below, when both players contribute the fund of science has a private (gross) value to each of $H(2)$. If a single player contributes, the gross private value of the scientific pool is $H(1) < H(2)$. Note that if player 2 does not contribute ($s_2 = 0$) but player 1 does contribute ($s_1 = 1$) the former receives a payoff of $H(1)$. It is possible for each player therefore to ‘free ride’ on the contribution of the other. The pool of science is jointly beneficial and it is non-excludable.

In the pure textbook case of a public good the following assumptions are usually made:

(1) $H(1) - c < 0$ – the private benefit of a single contribution is less than its private cost.
(2) $2H(2) - 2c > 0$ – the joint ‘social’ benefit from two contributions is greater than its social cost. Given that the individuals are identical $H(2) - c > 0$ and the net private payoff is also positive.
(3) $H(2) - c < H(1)$ or $H(2) - H(1) < c$ – the private benefit accruing to a second contribution falls short of its private cost.

This set of assumptions produces the classic ‘free rider’ equilibrium. In a single shot game $s_i = 0$ is a dominant strategy for both individuals and no contributions are made.

An alternative model is to assume that

(1)* $H(1) - c > 0$ – the private benefit of the first contribution exceeds its cost and
(2)* $2H(2) - 2c > 2H(1) - c$ or $H(2) - H(1) > c/2$ – there remain joint gains to the second contribution.

This produces a ‘chicken game’. If player 1 contributes, it is better for player 2 to free ride but if player 1 free rides it is better for player 2 to contribute. There are two possible Nash equilibria in pure strategies where one player contributes and the other does not. Although the Nash equilibria in the ‘chicken’ version both involve some positive level of contribution, the social optimum is not achieved. The non-contributing player is not induced to add further to the common pool because his or her private gain is restricted to $H(2) - H(1) - c < 0$ and it is not possible to capture a sufficient portion of the full social value of a further contribution. The rest leaks away to the other party who gains an ‘external’ benefit $H(2) - H(1)$.

The literature on games suggests many refinements to these results. Games that are repeated with the same players and where strategy choices can be adjusted over time can yield different results. However, there is little doubt that general acceptance of the proposition that science would be underprovided without government subsidy relies on the basic public goods argument sketched above.

In Table 2 we adjust the contribution game to take account of the features that cast doubt on the status of science as a pure public good. The main point at issue is that each player cannot simply enjoy the benefits of another player's scientific effort ‘freely’. Absence of a contribution greatly reduces the ability of a scientist to use the pool created by others. To reflect this idea, Table 2 records the payoff to a non-contributing scientist attempting to ‘free ride’ as $\theta H(1)$ for $0 \leq \theta \leq 1$ where the parameter θ represents the degree of ‘publicness’ of science. If $\theta = 1$ science is a pure public good and the non-contributing scientist gains the same benefit from another's contribution as the person actually making it and without incurring any cost. If $\theta = 0$ a non-contributing scientist can gain no benefit from another scientist's contribution. This is the case of the pure contribution good. The benefits of the pool of science (S) can be jointly accessed – external benefits do occur, but they are experienced only by contributing scientists.

The re-conceptualisation of the science problem proposed here clearly changes the nature of the game substantially. There is, however, still a collective action problem. Consider first the case of the pure contribution good ($\theta = 0$). If $H(1) - c < 0$ and the private benefit of the first contribution falls short of its private cost, the best response to $s_1 = 0$ is $s_2 = 0$ and the best response to $s_1 = 1$ is $s_2 = 1$. The payoffs no longer represent a ‘prisoner's dilemma’ as in the public good model of science, but a game of ‘pure coordination’. In other words each scientist needs reassurance that the other will contribute–not because there is a free rider problem but a ‘critical mass’ problem. If the team is not big enough there will be no private (or social) gains available. A single contribution yields no private

Table 1
Science as a public good.

		$s_2 = 1$		$s_2 = 0$
		$H(2) - c$		$H(1)$
$s_1 = 1$	$H(2) - c$		$H(1) - c$	
		$H(1) - c$		0
$s_1 = 0$	$H(1)$		0	

Table 2
Science as a contribution good.

		$s_2 = 1$		$s_2 = 0$
		$H(2) - c$		$\theta H(1)$
$s_1 = 1$	$H(2) - c$		$H(1) - c$	
		$H(1) - c$		0
$s_1 = 0$	$\theta H(1)$		0	

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gain with $H(1) - c < 0$ and neither is there a social gain because the benefit no longer spills over to the non-contributing scientist.

There are two equilibria in pure strategies to this game – one where both scientists contribute, and one where neither contribute. It is natural to ask therefore what conditions are likely to favour the co-operative outcome of mutual contribution. Clearly, a scientist who is certain that the other will contribute will also contribute. Even a reasonable level of confidence might be sufficient to induce a contribution. Indeed a risk neutral scientist believing that the other was as likely to contribute as not contribute would play $s = 1$ providing that

$$1/2[H(2) - c] + 1/2[H(1) - c] > 0 \quad \text{or}$$
$$H(2) > 2c - H(1) \quad \text{(i) or}$$
$$[H(2) - c] > -[H(1) - c] \quad \text{(ii)}$$

Expression (i) implies that both scientists will contribute providing that the private payoff to each $H(2)$ exceeds the sum of all private costs ($2c$) minus the gross private payoff to a single contribution. In the special case of $H(1) = 0$ this clearly reduces to $H(2) > 2c$ – a result discussed in Myatt and Wallace (2009, p. 66) in the context of a game in which output of a public good below a quota is destroyed in order to encourage private contributions. In this (non-public good) case the benefit from a single contribution does not spill over to the other party so that a higher value of $H(1)$ makes the mutual contribution outcome more rather than less likely.

Expression (ii) reflects a slightly different perspective. Loosely, providing each scientist has 'more to gain than to lose' from contributing the contribution, will be made. More specifically, for any given level of private cost c and private benefit from the first contribution $H(1)$, the scientist is more likely to adopt a strategy $s = 1$ the larger is $H(2)$ and hence the larger is the external benefit conferred on the other contributor $H(2) - H(1)$. The reason is simply that the external benefit is entirely reciprocal, and a high level of external benefit conferred on the other scientist is matched by an equally high level of benefit received 'in exchange'. Although these externalities existed in the 'public good' model they were not reciprocal in quite the same sense. Here, each scientist enters an implicit exchange agreement. The 'price' of using and benefiting privately from the science of others is to make a contribution to the pool from which others can benefit. An environment rich in spillovers is very attractive to scientists who can take advantage of them, and offering their own work to the pool in exchange for these spillover benefits is the implicit deal that leads to the formation of the invisible college.

Consider now a case where $\theta > 0$. From Table 2 it can be seen that the 'free rider' equilibrium will exist if $H(2) - c < \theta H(1)$. In other words the 'science as a public good' model re-asserts itself if

$$\frac{H(2) - c}{H(1)} < \theta.$$

For sufficiently small values of θ however, the contribution game can be analysed as above. On the continued assumption that each scientist conjectures that the other is as likely to contribute as not to contribute, the co-operative outcome will require

$$[H(2) - c] - \theta H(1) > -[H(1) - c]. \quad \text{(ii')}$$

The invisible college forms if

$$H(2) > 2c - H(1)[1 - \theta] \quad \text{for } 0 < \theta < [H(2) - c]/H(1). \quad \text{(i')}$$

Instead of assuming a contribution probability of 0.5 and concentrating on critical values of the parameter θ an alternative approach is to calculate the probability (p) above which 'contribution' becomes the preferred strategy.

For risk neutral scientists, 'contribution' is the best strategy if the expected return exceeds the expected return to 'no contribution'. Thus

$$E(s = 1) = p[H(2) - c] + (1 - p)[H(1) - c] \text{ and}$$

$$E(s = 0) = p\theta H(1)$$

Thus contribution is the best strategy if $E(s = 1) > E(s = 0)$ or if

$$p > \frac{[c - H(1)]}{\{H(2) - H(1)[1 + \theta]\}}$$

If $\theta = 0$ and there are no spillovers to non-contributors this reduces to

$$p > \frac{[c - H(1)]}{H(2) - H(1)}$$

Clearly the critical value of p depends upon the size of the loss on a single unmatched contribution $c - H(1)$ relative to the size of the spillover from the second contribution $H(2) - H(1)$. The greater the external benefit, the lower is the critical probability p that will induce scientists to contribute. Where θ is small, spillovers between contributors encourage contributions. Conversely, for a given level of spillovers, contribution is more likely (the critical value of p is lower) the more nearly a single contribution approaches profitability.

Although in the case of two scientists this argument seems compelling and the cooperative solution therefore justified, it is clearly less persuasive if the coordination of a large number of scientists is required before mutual profitability is established. Where scientists do not contribute to the common pool it will be difficult to get them started whereas once the habit has been established it will become self-enforcing. Some 'visible college' is required to establish a minimum critical level of contribution.

Where $H(1) - c > 0$ and a single contribution is privately profitable, the situation is obviously much more favourable to invisible college formation. Continuing to assume that $H(2) - c > \theta H(1)$, so that spillovers to non-contributors are sufficiently small, strategy $s = 1$ is in this situation a dominant strategy. The limited extent of spillovers to non-contributors turns a game of chicken into one in which a collective action problem no longer exists.

Within-college externalities exist in this formulation but the absence of a contribution margin – the inability of a scientist to vary at some marginal cost the amount contributed – dissolves the collective action problem once the private profitability of the discrete contribution is established. In the sections that follow we continue investigating the case of discrete contributions. However, in Section 4 scientists are assumed to vary in ability with high ability scientists contributing more to the pool (and able to benefit more from the pool) than low ability scientists. Before moving to this elaboration, Section 3 presents further analysis of the equal ability case.

3. The contribution good with scientists of equal ability

The main determining characteristic of a contribution good is that, although accessible in common (at some private cost) it can only be used by a person who has contributed in kind to its provision. This is capable of generating results quite different from those associated with a classic 'public good' framework.

Let all scientists be of equal ability a. The common pool of scientific knowledge is assumed to derive from the human capital of the scientists and can be written

$$S = na$$

where n is the number of scientists in the invisible college.[5] This pool of knowledge is available to all college members. Let each scientist use the pool as an input into economic activities that yield a rent (π) of

$$\pi = aH(S) - c$$

with $H'(S) > 0$ and $H''(S) < 0$ and where c represents an overhead cost of scientific activity for each scientist.

This rent (π) is assumed to represent the social surplus as well as the private return to the scientist. It is of course unlikely that any scientist would manage to appropriate the full social surplus derived from his or her use of the common pool. Much would be expected to leak away to others during the process of negotiation with the owners of cooperating inputs. Some might be lost as a result of 'rent seeking'. In this paper, however, we do not consider rent seeking losses and our theoretical results do not hinge on the precise proportion of the rent accruing to the scientist. Losses that derive from opportunistic behaviour or from lack of legal protection might severely restrict scientific activity. The existence of institutional structures that place limits on opportunistic behaviour and permit scientists to contract with financiers and others are necessary to the operation of this model. Simple failure to appropriate the entire available social surplus, however, would not have such a negative effect. Just as a tax on rent is theoretically neutral, the sharing of rents with other parties will give rise to income effects but not substitution effects.

Clearly if $aH(S) < c$ no rents can be achieved by individual scientists. As n increases however a point may be reached at which S passes the critical value at which $\pi = 0$ and all scientists can make positive economic rents from their use of the pool of knowledge. Let this value of n is given by n^*.

For values of n greater than n^*, rents are positive for all members of the invisible college and all members benefit from further entry. Thus, aggregate rents (W) increase without limit as the invisible college 'explodes'.

Consider for example, the case of $H(S) = \sqrt{S}$.

$$\pi = a\sqrt{S} - c$$

The critical value of n^* will be determined by $a\sqrt{S} = c$. Thus

$$\frac{c^2}{a^3} = n^*$$

The case is illustrated in Fig. 1.

Aggregate rents W are given by

$$W = n\pi(n) = na\sqrt{S} - nc = a^{1.5}n^{1.5} - nc$$

Thus

$$\frac{dW}{dn} = \pi(n) + n\pi'(n) = 1.5a^{1.5}n^{0.5} - c = (a^{1.5}n^{0.5} - c) + 0.5a^{1.5}n^{0.5} > 0$$

and

$$\frac{d^2W}{dn^2} = 0.75a^{1.5}n^{-0.5} > 0.$$

In other words new entry to the college produces rents for the marginal entrant of ($a^{1.5}n^{0.5} - c$) and confers positive (and increasing) aggregate external benefits on the other college members of ($0.5a^{1.5}n^{0.5}$). The marginal external benefit received by each existing college member declines as the college grows ($\pi''(n) < 0$).

This model clearly yields results that are extreme, but it serves to illustrate the potential power of a system which (in spite of extreme jointness in the availability of knowledge) requires the users of knowledge to add to the pool before useful access can be achieved. It also suggests a number of factors that will be important in determining the point of scientific 'take-off' into self-sustained accumulation to adapt Rostow's (1990) terminology. The invisible college requires a minimum membership to be sustainable. This number will be lower the greater is the ability level of the scientists (a) and the lower is the overhead cost of undertaking scientific work (c). For any given values of these parameters college formation will depend upon the transactions costs of forming a 'visible' college. Thus with no change in ability or in the cost of science, a fall in transactions costs might permit the formation of a college that would then have self-sustaining characteristics.

4. A model of the invisible college with variable ability

The basic model sketched in Section 3 assumes that additional scientific 'ability' does not decline but remains at a constant level. In Section 4 we make some adjustments to take into account both variable ability of scientists and bounds on the capacity of scientists of any particular ability to make use of an expanding pool of knowledge.

Let scientists vary in ability (a).

The frequency of ability a is given by

$$f(a) \quad \text{for } 0 < a < \mathbf{\hat{a}}$$

Let $\ddot{a}$ be the ability of the least able scientists in the college. The frequency of scientists of ability $\ddot{a}$ or above is therefore:

$$F(\mathbf{\hat{a}}) - F(\ddot{a}) = \int_{\ddot{a}}^{\mathbf{\hat{a}}} f(a)da$$

Total 'stock' of ability equal to or greater than $\ddot{a}$ is given by

$$S = \int_{\ddot{a}}^{\mathbf{\hat{a}}} af(a)da = \varphi(\ddot{a})$$

$$\text{where } \varphi'(\ddot{a}) = -\ddot{a}f(\ddot{a}) < 0 \quad (1)$$

We continue to suppose that the scientific knowledge available for exploitation can be measured by the 'ability' of the contributing scientists and that $\varphi(\ddot{a})$ can be interpreted as a common 'pool' of knowledge. Each scientist must invest c in order to gain access to this pool of scientific knowledge (a pool that will contain his or her own contribution). The 'rent' of each scientist from the exploitation of the common pool is assumed to depend directly on ability. Thus

$$\pi(a, \ddot{a}) = aH[\varphi(\ddot{a})] - c \quad (2)$$

where H is a function describing the terms on which the pool of scientific knowledge deriving from the aggregate human capital embodied in the contributing scientists can be transformed into revenue yielding economic output.

We assume $H' \geq 0$; $H'' \leq 0$.

[5] If the common ability level of scientists is set equal to unity, this formulation starkly reveals that the size of the common pool of knowledge is simply given by the number of contributing scientists, or (when ability is allowed to vary) by some weighted sum of the contributing scientists. It can be objected that measuring the pool of science in this way suppresses any reference to the enormous variety of contributions. An analogy would be measuring the resources of a museum or art gallery by the number of its exhibits without reference to the historical periods represented or the physical nature of the items. For the purposes of gaining an initial insight into the contribution good framework, however, the use of this very simple measure of the common pool is convenient. Further work using more refined and multi-faceted measures of the pool of scientific contributions, with degrees of spillover varying within and across disciplines, might cast much further light on the model as well as on its possible implications for science policy.

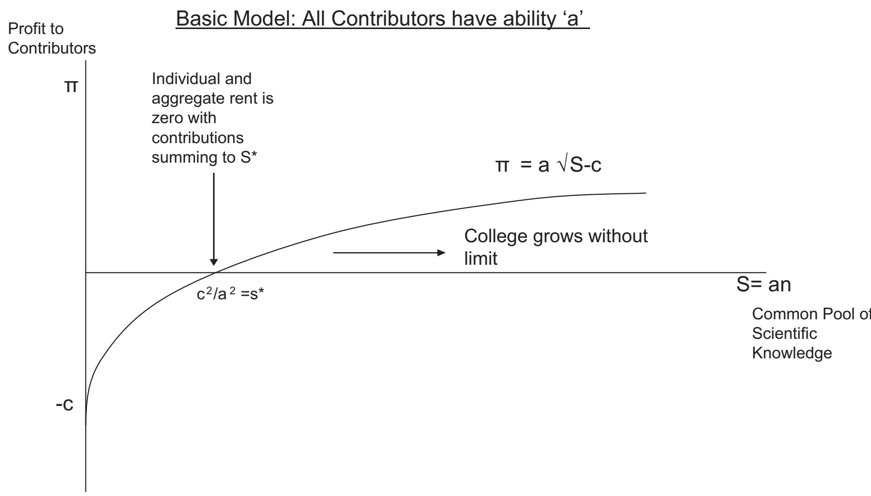

Fig. 1. Basic model: all contributors have ability '*a*'.

It follows that privately appropriated rent rises with ability because more able scientists make more productive use of the common pool:

$$\frac{\partial \pi(a, \ddot{a})}{\partial a} = H[\varphi(\ddot{a})] > 0. \quad (3)$$

The rent of a person of any given ability declines as the ability level of the least able member of the invisible college rises (because a higher level of $\ddot{a}$ implies a smaller size of college and a smaller pool of common resources available to be exploited).

$$\frac{\partial \pi(a, \ddot{a})}{\partial \ddot{a}} = aH'[\varphi'(\ddot{a})] \leq 0 \quad (4)$$

The rent of the least able members of the college will be

$$\pi_{\ddot{a}}(\ddot{a}) = \ddot{a}H[\varphi'(\ddot{a})] - c \quad (5)$$

Thus

$$\frac{\partial \pi_{\ddot{a}}}{\partial \ddot{a}} = \ddot{a}H'[\varphi'(\ddot{a})] + H[\varphi(\ddot{a})]$$

Or:

$$\partial \pi_{\ddot{a}}/\partial \ddot{a} = \partial \pi(a, \ddot{a})/\partial \ddot{a} + \partial \pi(a, \ddot{a})/\partial a$$

$$(a = \ddot{a})$$

The change in the rent of the least able college member as marginal ability rises is made up of two components. Rent achieved by the least able (along with all other scientists) is reduced because the common stock of scientific knowledge available $\varphi(\ddot{a})$ declines when scientists of lesser ability are no longer contributing. This is offset by the fact that the least able scientist now has higher ability and therefore obtains a greater gain from any given stock.

For $\pi_{\ddot{a}} = \ddot{a}H[\varphi(\ddot{a})] - c > 0$ scientists of lesser ability will continue to enter until rents are zero at the margin.

Thus:

$$\pi_{\mathbf{\mathring{a}}} = \mathbf{\mathring{a}}\, H[\varphi(\mathbf{\mathring{a}})] - c = 0 \quad (6)$$

is an equilibrium condition for the size of the invisible college where $\mathbf{\mathring{a}}$ is the ability level of the scientists capable of just making zero rent (the marginal scientists).

Re-arranging (6)

$$H(\varphi(\mathbf{\mathring{a}})) = \frac{c}{\mathbf{\mathring{a}}}$$

This equation could be satisfied at several values of $\mathbf{\mathring{a}}$ – high marginal ability and a small pool of scientific knowledge ($\mathbf{\mathring{a}_H}$) and low marginal ability with a relatively high pool of scientific knowledge ($\mathbf{\mathring{a}_L}$). Where the rent of the marginal scientist is growing with further entry ($\partial \pi_{\ddot{a}}/\partial \ddot{a} < 0$), the zero profit condition will not be a stable equilibrium. It will, however, represent the minimum self-sustaining size for the 'invisible college' ($\mathbf{\mathring{a}_H}$). Where profits of the marginal scientist are declining with further entry ($\partial \pi_{\ddot{a}}/\partial \ddot{a} > 0$) the zero profit condition will represent a stable equilibrium and the marginal ability will be lower ($\mathbf{\mathring{a}_L}$).

Thus where $\ddot{a} = \mathbf{\mathring{a}_H}$

$$\frac{\partial \pi_{\ddot{a}}}{\partial \ddot{a}} = \mathbf{\mathring{a}_H} H'[\varphi'(\mathbf{\mathring{a}_H})] + H[\varphi(\mathbf{\mathring{a}_H})] < 0$$

and a larger college will result in higher profits to the marginal scientist.

This implies

$$(\mathbf{\mathring{a}_H})H'[\varphi'(\mathbf{\mathring{a}_H})] + \frac{c}{\mathbf{\mathring{a}_H}} < 0 \quad \text{(from 6)}$$

or

$$c < (\mathbf{\mathring{a}_H})^3 f(\mathbf{\mathring{a}_H})H' \quad \text{(using 1)}$$

For a stable equilibrium where $\ddot{a} = \mathbf{\mathring{a}_L}$

$$\partial \pi_{\ddot{a}}/\partial \ddot{a} > 0 \text{ and}$$

$$c > (\mathbf{\mathring{a}_L})^3 f(\mathbf{\mathring{a}_L})H'.$$

For $\mathbf{\mathring{a}_L} < \ddot{a} < \mathbf{\mathring{a}_H}$ all contributions are privately profitable and the invisible college will grow. Before achieving the critical mass implied by $\ddot{a} = \mathbf{\mathring{a}_H}$ (i.e. where $\ddot{a} > \mathbf{\mathring{a}_H}$) however, scientists face the collective action problem discussed in Section 2 of ensuring that enough high ability contributors take part in order for the private payoff to be positive. If there is complete confidence that the threshold $\mathbf{\mathring{a}_H}$ will be achieved, further growth will be self-sustaining until marginal ability has declined to $\mathbf{\mathring{a}_L}$. Unlike the model presented in Section 3 there is a limit to the growth of the invisible college as lower ability levels eventually cause the cost c to exceed the private benefits achievable from college 'membership' by the marginal scientists.

5. Aggregate college rents

Social rents generated are the sum total of all private rents.

$$\int_{\ddot{a}}^{\mathbf{\mathring{a}}} \pi_a f(a)da = W(\ddot{a})$$

Thus

$$W(\ddot{a}) = \int_{\ddot{a}}^{\hat{\mathbf{a}}} af(a)H[\varphi(\ddot{a})]da - c\int_{\ddot{a}}^{\hat{\mathbf{a}}} f(a)da$$

or

$$W(\ddot{a}) = H[\varphi(\ddot{a})]\int_{\ddot{a}}^{\hat{\mathbf{a}}} af(a)da - c\int_{\ddot{a}}^{\hat{\mathbf{a}}} f(a)da \quad (7)$$

$$W(\ddot{a}) = H[\varphi(\ddot{a})]\varphi(\ddot{a}) - c[F(\hat{\mathbf{a}}) - F(\ddot{a})]$$

$$\partial W(\ddot{a})/\partial\ddot{a} = H[\varphi(\ddot{a})]\varphi'(\ddot{a}) + \varphi(\ddot{a})H'[\varphi'(\ddot{a})] + cf(\ddot{a})$$
$$\partial W(\ddot{a})/\partial\ddot{a} = -\ddot{a}f(\ddot{a})H[\varphi(\ddot{a})] - \ddot{a}f(\ddot{a})\varphi(\ddot{a})H' + cf(\ddot{a}) \quad (8)$$

Increasing the lowest ability level of scientists in the college loses the rents accruing to that group:

$$-\pi_{\ddot{a}}f(\ddot{a}) = -\{\ddot{a}f(\ddot{a})H[\varphi(\ddot{a})] - cf(\ddot{a})\}. \quad (9)$$

It also reduces the profits of scientists in the higher ability ranges:

$$\int_{\ddot{a}}^{\hat{\mathbf{a}}} \left(\frac{\partial\pi}{\partial\ddot{a}}\right) f(a)da = H'[\varphi'(\ddot{a})]_{\ddot{a}}\int_{\ddot{a}}^{\hat{\mathbf{a}}} af(a)da = \varphi'(\ddot{a})\varphi(\ddot{a})H'$$
$$= -\ddot{a}f(\ddot{a})\varphi(\ddot{a})H' \quad (10)$$

Eq. (10) expresses the usual external effect of changes in scientific effort. Reduced work by scientists of lesser ability results in a smaller stock $\varphi'(\ddot{a}) = -\ddot{a}f(\ddot{a})$ of scientific knowledge and this decrement can no longer be used by the human capital remaining $\varphi(\ddot{a})$. The external consequence is less significant if H' is small and further scientific work is of low potential productivity even when interpreted and used by the most able people.

For $H' > 0$, this externality produces the usual result that the equilibrium size of the invisible college is suboptimal. At $\ddot{a} = \mathring{\mathbf{a}}$ the rent of each marginal scientists is zero ($\pi_{\mathring{a}} = 0$) and hence (from Eqs. (8) and (9))

$$\partial W(\ddot{a})/\partial\ddot{a} = -\mathring{\mathbf{a}}\, f(\mathring{\mathbf{a}})\varphi(\mathring{\mathbf{a}})H' \le 0$$
$$(\ddot{a} = \mathring{\mathbf{a}})$$

Aggregate rents would increase by using additional less talented scientists. Maximisation of W requires

$$\frac{\partial W(\ddot{a})}{\partial\ddot{a}} = -\ddot{a}f(\ddot{a})H[\varphi(\ddot{a})] - \ddot{a}f(\ddot{a})\varphi(\ddot{a})H' + cf(\ddot{a}) = 0.$$

If this equation is satisfied at $\ddot{a} = \tilde{\mathbf{a}}$ the losses, at maximum W assumed greater than zero, of scientists with ability such that $\tilde{\mathbf{a}} \le a < \mathring{\mathbf{a}}$ are more than offset by the positive rents of scientists for whom $\mathring{\mathbf{a}} \le a \le \hat{\mathbf{a}}$. In other words, the optimum requires a visible college to redistribute rents from the more able towards the less able.

Eq. (8) also indicates that as c declines towards zero scientists of lesser ability should join the college and that with $c = 0$ scientists of all abilities should be used. With $cf(\ddot{a}) > 0$ however, a sufficiently low level of ability $\ddot{a}$ will imply $\partial W(\ddot{a})/\partial\ddot{a} > 0$ and the college should optimally shrink its membership.

6. An illustrative special case

Let the scientists be uniformly distributed between $a = 0$ and $a = \hat{\mathbf{a}}$ with $f(a) = 1$. Let there be no diminishing returns to additions to the scientific pool so that $H[\varphi(\ddot{a})] = \varphi(\ddot{a})$ and $H' = 1$.

$$S_{\ddot{a}} = \int_{\ddot{a}}^{\hat{\mathbf{a}}} af(a)da = \varphi(\ddot{a}) = \frac{1}{2}(\hat{\mathbf{a}}^2 - \ddot{a}^2)\text{ and }\varphi'(\ddot{a}) = -\ddot{a}. \quad (1')$$

$$\pi_{\ddot{a}} = \ddot{a}H[\varphi(\ddot{a})] - c = \left(\frac{1}{2}\right)\ddot{a}(\hat{\mathbf{a}}^2 - \ddot{a}^2) - c \quad (5')$$

Thus

$$\frac{\partial\pi_{\ddot{a}}}{\partial\ddot{a}} = \ddot{a}H'[\varphi'(\ddot{a})] + H[\varphi(\ddot{a})] = -\ddot{a}^2 + \frac{1}{2}(\hat{a}^2 - \ddot{a}^2)$$

and $\partial\pi_{\ddot{a}}/\partial\ddot{a} = 0$ at $\ddot{a} = \pm\hat{\mathbf{a}}/\sqrt{3}$.

The cubic Eq. (5′) must have two positive roots if an invisible college is to be sustainable. If there are no positive roots, the overhead costs to each scientist of engaging in scientific activity are at all points too great to permit positive rents to be made by the marginal scientist. In such a case there might still be positive aggregate rents to scientific effort but capturing them would require the formation of a visible college. Without redistribution within the college and a method of rewarding scientists for external benefits conferred on others, loss-making scientists would leave and the college would collapse. The situation would be close to the traditional 'public good' model of science.

Eq. (5′) is shown diagrammatically in Fig. 2. The figure includes negative values of $\ddot{a}$ but these are clearly not relevant for our purposes. Using the figure it is possible to see that the contribution good model proposed here does not escape entirely from the traditional dilemmas. If the most able scientists cannot on their own achieve positive rents of ability, gaining the social benefits of scientific enquiry must require the pooling of scientific knowledge. The problem is to explain how this pooling comes into existence.

Some 'visible' hand is required to devise institutions that encourage scientific endeavour. This could be envisaged as an unintended outcome of some other activity or as a conscious decision by a group of scientists to form a college or society. The problem, it will be recalled, is not reluctance to contribute to the common resource in order to 'free ride' on the work of others, but to establish confidence that enough other scientists of sufficient ability will join the college to make the investment of c worthwhile. For values of $\ddot{a}$ (the least able college member) greater than $\mathring{\mathbf{a}}_{\mathbf{H}}$ it can be seen that the college is too small for this least able scientist to derive positive rents from use of the common pool. Aggregate college rents, however, are positive at a value of $\ddot{a}$ greater than $\mathring{\mathbf{a}}_{\mathbf{H}}$. Clearly $W(\ddot{a} = \mathring{\mathbf{a}}_{\mathbf{H}}) > 0$ since $\partial\pi(a, \ddot{a})/\partial a > 0$ and all college members apart from the marginal ones are therefore achieving strictly positive rents. Thus $W(\ddot{a}) = 0$ at a value of $\ddot{a}$ greater than $\mathring{\mathbf{a}}_{\mathbf{H}}$. For all college members to benefit from the pool at these smaller college sizes however, there would have to be some sharing mechanism until the critical size implied by $\ddot{a} = \mathring{\mathbf{a}}_{\mathbf{H}}$ had been achieved.

Fig. 2 illustrates the point that a sufficiently high value of c can result in the absence of any positive real roots to the equation of $\pi_{\ddot{a}}$ and hence the impossibility of a self-sustaining invisible college. Clearly there will be some value of c such that there is a repeated root and (again given $\partial\pi(a, \ddot{a})/\partial a > 0$) this will imply that a visible college could produce positive aggregate college rents. Indeed even higher cost levels would have to be assumed before both visible and invisible colleges became unsustainable at any college size.

The expression for aggregate rents in this special case is

$$W(\ddot{a}) = \left[\frac{1}{2}(\hat{\mathbf{a}}^2 - \ddot{a}^2)\right]^2 - c(\hat{\mathbf{a}} - \ddot{a}). \quad (7')$$

Similarly

$$W'(\ddot{a}) = -\ddot{a}\left[\frac{1}{2}(\hat{\mathbf{a}}^2 - \ddot{a}^2)\right] - \ddot{a}\left[\frac{1}{2}(\hat{\mathbf{a}}^2 - \ddot{a}^2)\right] + c \quad (8')$$

These expressions are written so as to permit easy comparison with (7) and (8). Eq. (8′) draws attention to the fact that, in this case, the loss of revenue to the marginally excluded scientist when ability increases is precisely equal to the resulting aggregate loss in revenue over all the other ability levels. This, of course, derives from the fact that the revenue to each scientist is simply the product of his or her ability and the aggregate stock. The loss to all the other scientists combined when a person of ability $\ddot{a}$ leaves the college

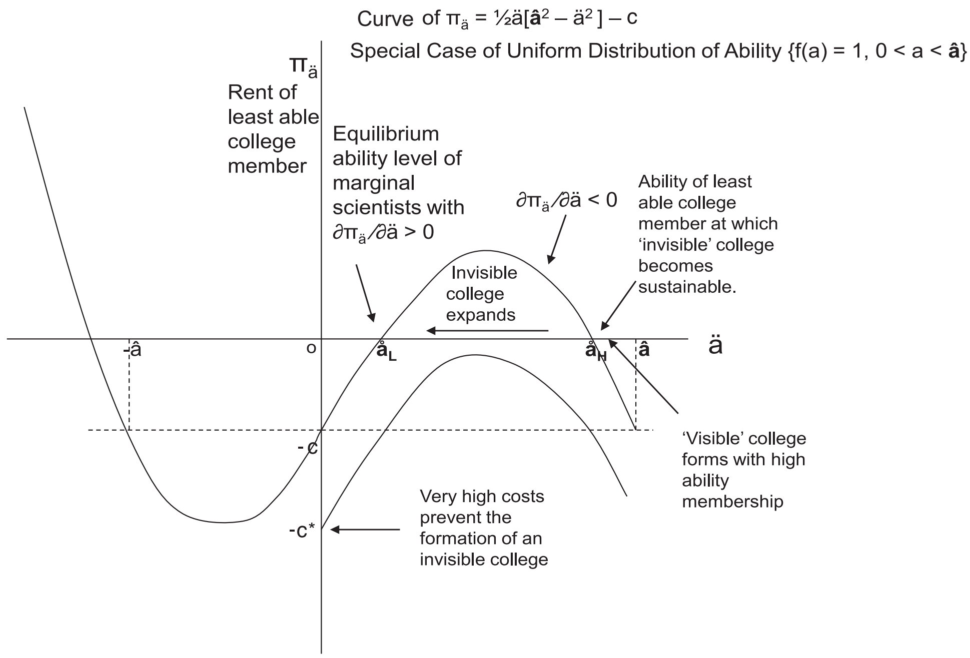

Fig. 2. Curve of $\pi_{\ddot a} = ½\ddot a[\hat{\mathbf a}^2 - \ddot a^2] - c$. Special case of uniform distribution of ability $\{f(a) = 1, 0 < a < \hat{\mathbf a}\}$.

is thus the same product – where $\ddot a$ is the decrement in the stock available to all the remaining scientists.

The loss of rents to existing scientists as the college contracts is

$$\int_{\ddot a}^{\hat{\mathbf a}} \left(\frac{\partial \pi_a}{\partial \ddot a}\right) da = \int_{\ddot a}^{\hat{\mathbf a}} (-a\ddot a)da = -\ddot a\left[\frac{1}{2}(\hat{\mathbf a}^2 - \ddot a^2)\right]. \qquad (10')$$

Conversely, as the marginal ability level declines with college expansion the external benefit to other scientists of new members will decline towards zero. Optimally the college should expand to the point at which these declining marginal external benefits just equal the losses incurred by the new members.

7. Discussion

7.1. Cultural norms in science and technology

Our proposed model of science as a contribution good relies on the distinction between 'open' science and 'privately appropriable' technology but does not see these two worlds as inhabited by non-overlapping groups of people with entirely separate customs and norms. Dasgupta and David (1994) also recognise that individual scientists can span both worlds but argue that maintaining a suitable dynamic balance between the two represents a major challenge for science policy. In particular science and technology are 'two distinctively organised and functionally differentiated spheres' (p. 517) and open science 'is constantly in need of shoring up through public patronage' (p. 514) without which 'sooner or later, economic progress almost certainly would lose the sustained character that has been taken by many scholars to distinguish ours from previous historical epochs' (p. 515). Universities for example confer great external benefits on technology by socialising students in the norms of open science and enabling them to signal their talents to the technological sector which will ultimately employ many of them.

The 'contribution' good framework leads to much less emphasis on the necessity of functional differentiation between the two spheres and suggests a somewhat different standpoint from which to view Robert Merton's (1942) work on 'The Normative Structure of Science'.[6] We would argue that the communalism and disinterestedness apparently associated with science can be seen as deriving from the assumed conditions of the contribution game itself whereby spillovers accrue mainly to contributors. Ultimately such communalism is buttressed by self-interest. The norms now associated with science evolved over a long period and pre-date large scale public patronage. Shapin and Schaffer (1985) show how the Royal Society of London, the world's oldest surviving research society, was founded in 1660 for the purposes of promoting the non-exclusion of science, and they describe how the Royal Society developed the convention of 'priority' by which esteem goes to the scientist who actually publishes first.[7] The conventions developed by the Royal Society towards the end of the seventeenth century might on occasion disadvantage an individual fellow by requiring the sharing of scientific knowledge but each fellow would be systematically advantaged by accessing the details of the work of the others. Self-interest was ultimately better served by being within the Society rather than outside it. A relatively small scientific world would have permitted the most able scientists to use social pressure to encourage membership and enforce conventions[8]

[6] Merton described modern science as being characterised by the acronym CUDOS which represented (i) communalism (by which scientists share knowledge voluntarily), (ii) universalism (by which claims to truth are judged by impersonal criteria, (iii) disinterestedness (by which scientists appear to act selflessly), and (iv) organised scepticism (by which ideas are scrutinised collectively.)

[7] The convention was also established that papers are accepted for publication only if they contain a methods section as well as a results section, to allow reproducibility. These conventions were in stark contrast to the preceding era in which scientists often expended considerable effort in attempts to maintain secrecy. Some scientists, having dated the report of a discovery, would seal and deposit it with a college or lawyer, only to open it to dispute priority when a later competitive publication appeared. Others would publish in code or in anagrams. Galileo, for example, revealed his discovery of the rings of Saturn in 1610 as *smaismrmilmepoetaleumibunenugttauiras* for *Altissimum planetam tergeminum observavi* (I have observed the most distant planet to have a triple form) while Robert Hooke revealed his law of elasticity in 1660 as *ceiiinosssttuv* for *ut tensio sic vis* (stress is proportional to strain).

[8] Echoes of these conditions continue even today. Many learned societies are run on club lines, with potential members being nominated and seconded before their memberships are voted upon.

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while the social status associated with college membership would also have skewed communications away from those outside thus further handicapping any attempt to free ride.[9] We could regard this as a period in which a visible college was required to assemble a critical mass of scientific talent.

The modern republic of science is far removed, of course, from the initial conditions found in 17th century London, and it is reasonable to ask whether its expanding population and spontaneously widening frontiers might undermine its founding values. Ultimately this would seem to depend on how far these values are self-enforcing within an 'invisible college' because of the tacit nature of much scientific knowledge. Some evidence is consistent with the hypothesis that openness is self-enforcing. Within industry some studies have found a correlation between the peer-reviewed publication rates of scientists and company profit, while Mansfield (1980) and Griliches (1986) showed that there was a direct correlation between firms' investment in basic research (a proxy perhaps for the amount of scientific ability devoted to science within the firm) and their profitability. Freeman and Soete (1997) estimated that some 7 per cent of industrial R&D worldwide is spent on basic science. As Hicks and Katz (1997) showed, this industrial investment in basic science translates into substantial rates of publication in the academic peer-reviewed literature, with major companies equalling the publication rates of medium-sized universities. Stephan (1996) discusses how companies balance the needs of publication against the need for proprietary information while business case studies reveal how older companies such as Dupont learned from their own experience that a policy of secrecy is not necessarily the most profitable – a lesson that newer companies such as Genentech internalised when they were founded with a very free publication policy. The idea that spillovers asymmetrically favour contributors over free riders is however, central to the entire contribution good model and further empirical work is necessary to ascertain how robust and widespread such conditions are.

7.2. *Science and the firm*

The contribution good model requires that scientists are able to gain financial rewards from the common pool of science. The institutional mechanisms that enable these rewards to be claimed are not modelled explicitly but are simply assumed to exist. The contribution good model of science has direct relevance, therefore, for research programmes in business structure and organisation. In modern Institutional Economics the firm is seen (i) as a substitute for relatively high costs of transacting in the market, after Coase (1937); (ii) as a means of coping with uninsurable uncertainty and continual change, after Knight (1921); and (iii) as a vehicle for instigating technological innovation, after Schumpeter (1934, 1943).[10] The conversion of scientific knowledge into new tradable goods and services confronts obvious transactional difficulties between scientists and technologists, technologists and entrepreneurs, and entrepreneurs and financiers. Cooperation between these elements entails high costs of transacting and is likely to involve the formation of firms with internal labour markets and specially designed incentive arrangements to mitigate them. Hansmann's (1996) proposition that ownership rights tend to be assigned to the group that faces the highest transactions costs might suggest, for example, the development of scientist-owned firms or firms with significant control rights in the hands of the knowledge creators and users.

The science-technology link is particularly pertinent to the functional separation that Dasgupta and David see as necessary to the maintenance of a suitable 'synergistic equilibrium'. The complementarities between science and its applications and the transactional difficulties of linking them across markets, would imply some advantages to integration.[11] Firms could not, in our pure contribution good world, specialise in pure research because their results would not be tradable and revenues are ultimately derived from the products of technology. Thus integration is, so to speak, inherent in our approach. Within the firm, however, there would still be problems of managing the science-technology interface if the people involved were specific and still 'functionally separated'. The model we have presented assigns a particular level of ability to each scientist and this ability represents both the additional 'contribution' to the pool of scientific knowledge and the scientist's skill at turning the pool to commercial advantage. Clearly, the relation in a scientist's work between his or her 'contribution' to the common pool of science and the ability of the scientist to use the whole pool to generate commercially valuable technology might vary. 'Contribution' would always be implied – but it might not be related to the ability to apply science to profitable technology.

Science is a common resource in our model, and firms will be interested in gaining access to the combined contributions of all scientists. It is, however, the ability of scientists in the area of technology that will determine whether or not they can operate profitably. Thus, in our 'contribution good model', the pool of science will be made up from the contributions of the best and most entrepreneurial in the realm of technology rather than simply the best 'scientists' (defined as those conferring the greatest external benefits on other college members). If these rather different abilities (contributing to the republic of science and using it for private gain) were independently and randomly distributed between scientists, there would be no expected loss to the pool of 'science' from selecting the best 'technologists' to comprise the college. On the other hand if it could be shown that (for example) the scientific contributions with the greatest potential tended to be made by people with relatively limited abilities in technology there would be a tendency to use 'too few' of these people (even in the unlikely event that they could provide an ex ante signal of their ability). Again, within the firm, teams of scientists with varying strengths could cooperate, and internalise some of the externalities (a possible advantage for large and diversified firms)[12] and across firms cooperative 'industry' or 'sector' research establishments might evolve as a result of mutual agreement. These comments are offered,

[9] Insiders could however use their reputational advantage to free ride on the work of outsiders. William Smith's geological map of England (1815) was published without proper acknowledgement by the Geological Society of London (1819). 'British scientists of an era long past behaved quite unforgivably towards one who was so self-evidently not one of their own' (Winchester, 2001, p. 223).

[10] Some of this literature has developed a highly critical view of standard 'optimising' models in economics and instead emphasises evolutionary methods with 'boundedly rational' decision makers adjusting to emerging information generated within the firm and outside. Major examples include Nelson and Winter (1982), Casson (2001), Kay (1979), Teece (1992) and Foss (1993). Recent contributions, for example, Teece (2007) have emphasised the development within the firm of 'dynamic capabilities' linked to human capital, internal and external information networks and entrepreneurial skills. The influence of Schumpeter's work is pivotal and has led to a literature on 'neo-Schumpeterian Economics'. Hanusch and Pyka (2007, p. 2) outline the main tenets of this paradigm as a concern with competition in innovation rather than in price, and recognition that this competition 'often occurs between networks of actors, where new knowledge is created and diffused collectively'. Instead of the public good conception of knowledge 'the tacit, local, and complex character of knowledge are emphasized' (p. 3).

[11] Teece (1988, p. 277), for example, writes that 'The natural organisational home for research appears to be inside the corporation, alongside production/operations'. The reasons are the richness of information flows within the corporation and the problem of writing R and D contracts.

[12] For example Kay (1988, p. 285) and Nelson (1959).

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however, to show that our proposed model of science requires suitable institutional mechanisms to exist for the spontaneous development of the 'invisible college' to take place and that these mechanisms relate closely to much recent work on the way that organisations are structured to encourage and manage scientific and technological change.

7.3. College formation, subsidies and growth

Although our model is not specifically designed to investigate public policy, it does allow us to analyse the effects of subsidies on science, assuming that subsidies reduce the cost to each scientist of engaging in scientific work and assuming that subsidies effectively pay the implicit entry fee to the college.

If no college exists, whether visible or invisible, action from whatever source that reduces C will lower the size of college at which aggregate rents to the members become positive. In the initial stages we might surmise that the transactions costs associated with college formation are substantial and that subsidies could be seen as a means of overcoming them. An analysis in the spirit of Coase (1937) would therefore look at the factors that might reduce transactional impediments to college formation over time.

The simple model proposed here does not lead to the conclusion that state subsidy is a necessary condition either for college formation or for its subsequent growth. It merely draws attention to the well-understood proposition that, in the presence of external effects, social benefits will accrue from the evolution of institutions capable of internalising them. The state subsidy of science could in pure logic (and ignoring all public choice considerations) represent one way of creating initial conditions suitable for the incubation of scientific advance. Aristocratic or philanthropic subsidy might achieve the same, whereas private governance might similarly be capable of producing a scientific college for sufficiently low values of c – rather as Ostrom (1990) shows that local institutions have evolved to handle environmental externalities.

The history of scientific colleges in the west confirms that their founding often did require subsidies, either from the state or from aristocrats. One of the world's first scientific academies, the Accademia dei Lincei (literally the "Academy of the Lynx-Eyed", the lynx having famously acute vision) was created in Rome by a small group of aristocrats in 1603. Social connections and wealth played an important role in establishing the Academia although it failed to achieve a self-sustaining character and did not move into our phase of spontaneous growth to a stable size. Indeed, after the Accademia's leader, Frederico Cesi, died in 1630, the Accademia itself died soon afterwards.

The Royal Society in London was created by a similar group of aristocrats, amongst whom Robert Boyle was prominent for his wealth and leadership. But other countries have seen their governments create their first academies. Thus the French Academy of Sciences was created in 1666 by Louis XIV on the suggestion of Colbert, while the National Academy of Sciences in the USA was created by Congress in 1863. It was foreshadowed, though, by a less visible, more Ostromian, college, the Lazzaroni, which was a club created in 1851 by Alexander Bache, who was the superintendent of the Coast Survey and the great-grandson of Benjamin Franklin, and who was to be the National Academy's first president. Over the last 300 years in the west, therefore, it appears that either wealthy aristocrats or governments have contributed to scientific advance by implicitly or explicitly reducing the costs of college formation.

Once a scientific community or 'college' reaches a particular minimum size, our model suggests that a 'take-off' occurs and the invisible college grows spontaneously. Lowering the costs of science to the participants will extend the college further and traditional theory would recommend a subsidy equal to the external benefits conferred by additional members on the incumbents.

If each scientist receives a subsidy

$$\sigma = \mathring{\mathbf{a}}\,\varphi(\mathring{\mathbf{a}})H' \quad \text{where}\ \mathring{\mathbf{a}}\,H[\varphi(\mathring{\mathbf{a}})] - c + \sigma = 0$$

the college will expand to an optimal size. The subsidy here is in the tradition of Pigou (1938, p. 224) and analogous to his recommendation of a 'bounty' to industries characterised by 'decreasing supply price'. This would be a difficult and contentious figure to estimate empirically. In principle it could be financed by a tax on the rents of the membership of the invisible college – although this raises the question of how far an 'invisible' institution with no formal governance structure could give rise to a membership capable of yielding tax revenue to the state or of administering internal redistribution of rent.

Assuming that subsidies to science are financed not from the internal rents of the college members but from general tax revenue, public choice questions concerning the interests of the scientific community become relevant. In particular it is evident that, in our model of the invisible college, every scientist has a private interest in college expansion because $\partial\pi(a, \ddot{a})/\partial\ddot{a} \leq 0$ (Eq. (4)) and the most able scientists are those who stand to gain the most. Shrinking the college lowers the rents achieved at all ability levels and vice versa. There is clearly therefore a danger that access to public subsidies will result in expansion of the college beyond the theoretical optimum and that the final position will be no more efficient (or even less so) than the original invisible college equilibrium. The efficiency costs of the taxes levied to fund the subsidy will also reduce the optimal (second best) size of the college.[13]

The 'contribution good' model can therefore be seen to fit into a long-established tradition in economics – a tradition that even its founders recognised used 'static' tools of analysis that were imperfectly suited to the dynamic nature of its subject matter. Nevertheless we argue that treating science as a contribution good casts a useful light on the nature of spillover benefits and their consequences. It directs attention to the conditions necessary for the invisible college to form and to expand in the first place (the critical mass problem) as well as the institutional mechanisms that address this problem and that enable rents to be earned from the process of innovation. The marginal inefficiencies that might theoretically remain after the college has ceased to grow are those that have traditionally concerned public policy. As Metcalf (2007, p. 962) argues, however, this focus of policy has been misplaced and over several decades has already been subject to change. Instead of attempting to correct for market failures, the state should aim to set the conditions 'in which innovation systems can better self-organise'. This agenda would include 'effective bridging arrangements' between individuals in Universities and other institutions, encouraging collaborative research programmes, science parks, cluster developments, arrangements for technology transfer and so forth. By reducing the costs of access and by creating conditions conducive to scientists gaining increasing external benefits from the common pool of knowledge created by their various activities and associated contributions, this policy agenda has close affinities with the model proposed in this paper. The contribution good model of science provides a new framework for interpreting the evolution of scientific institutions and commercial organisations as well as the development of public policy.

[13] These concerns were expressed by Hall and Reenen (2000) who showed that tax credits induce firms to increase their expenditure on R&D, but who worried that "Lowering the cost of research might cause the firm to do too much. Even though the tax credit induces more industrial R&D than the lost tax revenue, it would not be a good idea, because one could have spent that tax revenue on some other activity, which had higher social return."

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