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HEART OF DARKNESS: MODELING PUBLIC-PRIVATE FUNDING INTERACTIONS INSIDE THE R&D BLACK BOX

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ABSTRACT

This paper is a first step toward closing the analytical gap in the extensive literature on the results of interactions between public and private R&D expenditures, and their joint effects on the economy. Econometric studies in this area report a plethora of sometimes confusing and frequently contradictory estimates of the response of company financed R&D to changes in the level and nature of public R&D expenditure, but the necessary theoretical framework within which the empirical results can be interpreted is seldom provided. A major cause of "inconsistencies" in the empirical literature is the failure to recognize key differences among the various policy "experiments" being considered – depending upon the economy in which they are embedded, and the type of public sector R&D spending that is contemplated. Using a simple, stylized structural model, we identify the main channels of impact of public R&D. We thus can characterize the various effects, distinguishing between short-run and long-run impacts that would show up in simple regression analyses of nominal public and private R&D expenditure variables. Within the context of our simple model it is possible to offer interpretations that shed light on recent cross-section and panel data findings at both high (i.e. national) and low (specific technology area) levels of aggregation.

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I. BLACK BOXES TYPICALLY HOLD MORE HEAT THAN LIGHT

The interior of the black box of technology by now has become increasing crowded with economists of various stripes, and although growing areas are illuminated by the accumulating results of their investigations, some large regions of darkness remain.[1] One of the darkest patches of terrain is the realm where public and private R&D interact. It is not that this "heart of darkness" has remained infrequently visited. Quite the contrary: a survey of the econometric literature (which we undertook in collaboration with Andrew Toole) has identified more than 50 papers, most of them quite recent, that seek to address in one way or another the issue of the nature of those interactions.[2] The fact that the question keeps being raised, however, is in this case symptomatic not only of the interest that attaches to it but of the elusiveness of a satisfyingly conclusive answer.

Quite obviously it is a matter of considerable importance for science and technology policy-makers to know whether government R&D expenditures and company-financed R&D investments behave like substitutes or like complements. Insofar as the rationale for government support of R&D rests on the presupposition that too little research would be performed were the private sector to be left to its own devices, intense concern surrounds the possibility that public allocations for that purpose are being substituted for investments that firms would otherwise undertake. There is, in short, a worry that private R&D may be "crowded out" and the use of taxpayers money rendered far less effectual than might be supposed in augmenting society's investment in generating technological progress.[3]

But, like other processes that occur inside "black boxes," economic research on this issue has tended to be accompanied by more heat than light. Many of the findings that the literature presently offers on the question of substitutes vs. complements seem diametrically at odds with one another. In good part that results from the fact that the problem is being approach in very different ways, at different levels of aggregation, and with econometric models whose specifications and estimation methods are not the same. Yet, it is also attributable in some part to the field's under-investment in sorting out the various possible channels of influence that may be involved, and in examining their

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[1] Edwin Mansfield justly was recognized as one among the handful of economists who pioneered systematic explorations, beginning in the 1950's, of the interior of the "black box" of technology. That evocative phrase has been employed by Nathan Rosenberg (1982) in alluding to economists general disinclination to explicitly examine technological specifics; and in urging that greater attention be directed to the economic and social processes determining relationships between productive inputs and outputs – whether for firms, industries or entire economies. Ed Mansfield, however, had not needed such encouragement.

[2] See David, Hall and Toole (1999, forthcoming in *Research Policy*). There is a vastly more extensive body of work in economics which deals with case studies of the impact of government research programs upon private R&D investment: among these, Mansfield (1991) and Leyden and Link (1992) exemplify the applications of methods of non-econometric quantitative assessments; whereas an historical case study approach has been adopted in National Research Council-CSTB (1999).

[3] The question should of course be viewed in the larger context of the political economy literature dealing with the critique of state intervention in the economy. For a theoretical treatment of the determinants of private funding of public goods, see, e.g., Bergstrom, Blume and Varian (1986). Diamond (1998) approaches the issue of "crowding out" of private funding for basic research from this wider perspective, and reviews the applied research on the relationship between government income transfers and private charitable donations. But only Kealey (1996) has goes so far as to contend that public R&D funding could be substantially replaced by a mixture of private *charitable* bequests and industrial expenditure for the support of basic science.

possible interactions within a more comprehensive equilibrium framework. This cannot be done without the aid of some structural models, however simplified they might be. Yet, such an approach has remained out of favor among empirical students of this issue.

Because the econometric literature devoted to this topic has proceeded so far towards the extreme of "measurement without theory," we believe that what is likely to prove most fruitful at this juncture is the provision of more structural guidance in making sense of the empirical findings. Indeed, this seems a necessary next step if we hope to sustain the productive momentum that was originally imparted to research in this area by Mansfield's pioneering contributions. Although we are primarily concerned here to articulate analytical issues, in what follows we have approached the development of an instructive theoretical apparatus by keeping in mind the virtues of striving for simplicity, robustness and transparency ? aiming ultimately to contribute to the practical formation of better economic policy.

II. WHY WORRY? IS R&D "CROWDING OUT" NECESSARILY BAD?

Before going to greater analytical lengths, and to further refinements of econometric specifications in order to establish whether complementarity rather than substitution prevails at the margin in the relationship between public and private R&D funding, it surely is worth pausing to consider this question: Should we really be so concerned if public research funding happened to displace private R&D expenditures? This simple, logically antecedent question hitherto does not seem to have been asked, let alone answered in the economics literature.

As a rule, inquiries into whether or not there is "crowding out" of private R&D by government contracts, or grants, begin from the traditional supposition that the effect of information spillovers is causing the private marginal rate of return to be lower than the social marginal rate of return. More strictly, they ask whether this is the case at a level of private investment that is "too small." Hence, there is a presumption that any further displacement of private R&D by the direct or indirect effects of public research programs must be a perversely bad outcome. This presumption accounts for the absence of explicit attention to the question of whether "crowding out" in this context is necessarily bad.

But, rather than simply positing that the problem of imperfect appropriability results everywhere in a deficiency of private R&D investment, we should stop to take notice of the extensive list of exceptions that qualify the conventional conclusion based on theoretical considerations. Racing behaviors, business stealing strategies, and "excess correlation" among companies' R&D programs, all constitute potential pathologies that stem from conditions that cause the expected private marginal rate of return to an individual firm's investments to exceed the marginal social rate on the R&D projects in question.[4] In such circumstances it is not implausible to suppose that the "excessive concentration" of private expenditures could drive down the social marginal rate of return on the R&D performed by the private sector. Indeed, it might depress the latter to levels

[4] See Dasgupta and Maskin (1987) on "excess correlation," and National Research Council (1999), esp. pp. 45-46, for further discussion of potential sources of private sector over-investment in R&D.

well below the social marginal rate on lines of research that the private sector was ignoring – possibly due to difficulties in appropriating the benefits fully.

The situation just envisioned bears some resemblance to the one famously diagnosed by J.K. Galbraith in *The Affluent Society* (1969), namely, excessive private (consumption) expenditures in the midst of public squalor; and so it conveniently might be labeled "the problem of the affluent knowledge society." Although we can put a catchy name to it, demonstrating that there is something worth naming is a greater challenge. The foregoing market pathologies have been attested to far more fully by discussions in the theoretical literature than by the empirical evidence.[5] We cannot presently say whether or not there is any substantial degree of correspondence between reality and the contemplated situations of (socially) excessive private investment in R&D. What such evidence as might be adduced in this connection tends to show is that R&D performance by some of an industry's firms' does *not* depress expected marginal rates of return enjoyed by other firms. At least, not sufficiently to drive down the realized average private rates of return, thereby lowering the social marginal return on their collective investments. This could very plausibly be so because competitors' R&D projects generally are of the sort that actually generate compensating beneficial spillovers, either in the form of additional scientific and technological knowledge, or information about the responses of buyers to the design properties of new products.

What possible policy implications would follow from the existence of excess correlation among private R&D strategies in specific areas? It is difficult to move forward towards generic policy prescription here, precisely because *ex hypothesis* the situation differs greatly between one research area and the next; the nature of the putative problem – if it does exist – is that some research areas are being over-funded, whereas other are under-funded. To think of attacking this by direct targeting of public research, aimed at "crowding out" just some private R&D expenditures and not others, would presuppose a degree of precision in the evaluation of the situation that does not presently exist, and is not likely to obtain.[6] One also would need to ascertain that the public sector was able to perform R&D in the targeted area with at least the same effectiveness as could be expected of a private firm.

Therefore, it may well be that the best instruments to address the problem where it does exist are those of an entirely different sort than the direction of public research resources. Where the structure of the payoffs is the source of wastefully duplicative private

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5 This issue recently has been examined at the aggregate level by Jones and Williams (1997). These authors conclude, on the basis of simulation results for an aggregate growth model, that it is quite unlikely for tendencies to over-investment to overwhelm those that would give rise to the opposite effect. Exceptions occur (in their model) under conditions that are readily intelligible: where the real rate of interest is very high, so that the value of knowledge spillovers enjoyed by future generations is heavily discounted, and where the marginal rate of return on additional R&D is very low.

6 This difficulty does not apply to a "preemptive strike" policy for the public sector, whereby research and patenting in a particular area could be undertaken for the purpose of preventing private agents from acquiring intellectual property rights to discoveries that might convey large external benefits were they to be freely licensed. The U.S. National Institute of Health actually experimented with a "preemptive" research and patenting strategy resembling this during the mid-1990's, in response to the efforts of a private company to file patents on fragmentary gene sequences.

research strategies and "socially excessive" expenditures directed toward hastening the completion research projects by small margins, then restructuring the expected payoffs would be the first-best-form of policy response. Failing that, however, altering the way investment tax credits are paid, so as to make the value of the latter diminish at the margin, would seem to be worth considering as a more promising line of corrective action.

Another area where "winner takes all" payoffs structures may be inducing inefficiently large private outlays for R&D may be seen in the ICT industries. Here there is reason to expect that major positive externalities would flow from greater progress towards network compatibility standardization. Nonetheless, there are ample indications that private firms are induced to direct much of their R&D primarily towards the generation of alternative basic system designs, and that the key factor in such decisions is the prospects of high rates of return from becoming the reigning *de facto* standards monopoly. This is the case particularly where such designs can be used to shift an existing customer base and impart bandwagon momentum to the "innovator's" marketing efforts. The result tends to be the co-existence in the market of excessive diversity of rival designs, none of which are manifestly technically superior, but which increase the uncertainty of adopters and so postpone the realization of the benefits of standardization. But here, as elsewhere, the remedy to consider first would appear to be a reduction of the incentives at the margin, possibility by weakening the intellectual property protection that the dominant *de facto* standard is now accorded under the prevailing interpretation of copyright and patent laws.

We may conclude that where crowding out might occur and yet not be deemed necessarily bad, such situations do not automatically make targeted public R&D expenditures into a good policy instrument. This reaffirms the basis for the policy-interest that adheres to answering the question of whether substitution or complementarity effects are dominant in the relationship between private and public R&D expenditures.

III. A SKETCH-MAP OF THE INTERIOR TERRITORY

We propose here a simple, but nonetheless analytically grounded taxonomic overview of the variety of possible impacts that the funding of R&D in the public sector may have upon the performance of company-financed R&D. At the outset it should be understood that the relationship of proximate concern to us is that between real levels of research expenditure in the two sectors. This focus follows from the fact that these are the variables that are most widely reported in official statistical sources over time, among different national economic entities, and across various areas of applied relevance. Moreover, those are the major variables upon which policy decisions in the public and private spheres are focused. Accordingly, for both of those reasons, the mass of the theoretical and econometric literature dealing with the role of government R&D funding has been directed to examining in the first instance how it affects the company-financed counterpart.[7]

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[7] A notable exception is the treatment by Leyden and Link (1991, 1992). They have sought to improve upon the state of the literature characterized in the following terms (1992: p.55): "Studies of government R&D allocation to private-sector firms have generally focused on the effects of such allocations on private-sector

A more comprehensive account would, of course, consider also influences that ran in the other direction – from private R&D funding decisions to government support of scientific and technological research. Yet that would necessarily carry the discussion into the realms of the political economy of science and technology policy formation, as well as the administration of public sector R&D contracts and intra-mural research project management. This would raise important and complex issues into which we cannot enter on this occasion. Even so, economists engaged in empirical studies of the effects of public expenditures for R&D would do well to bear in mind that the programs through which these are undertaken do not arise spontaneously. Far from existing in an economic vacuum, the specific purposes, organizational design and funding level in such programs reflect both political pressures and technical feasibility constraints. These are shaped by the past, current and anticipated R&D activities of private business, as well as by the perceived needs of government mission agencies. Although for the purposes of analysis we shall suppress all that and proceed as though the volume and composition of government R&D performed can be taken as being parametrically fixed by an exogenous policy process, that is not an empirical stipulation about the world. Instead, it is an abstraction from reality that remains to be justified as reasonable, or shown to be seriously misleading by future econometric studies.

Our framework has been structured along three taxonomic dimensions. To begin with we recognize two fundamentally different sets of channels through which the effects of interest can flow between the public and private sectors. The set first involves the direct effects upon the demand and supply of tangible resource inputs that are used in performing R&D. The second category of effects are indirect, so to speak, because they involve in the first instance the intangible results of the conduct of R&D, namely, the generation of new knowledge, and then the influence which the existence of such knowledge may have upon the expected costs and benefits of R&D financed by private business.

New knowledge may be made available in codified form, where it can be more cheaply transmitted and accessed by those who can "read the code;" or it may be "embodied" in the acquired expertise of research scientists and engineers. Such knowledge also may be embodied in artifacts, such as scientific instruments whose design prototypes emerge as by-products of specific research projects.[8] A convenient taxonomic convention that we find helpful in structuring the following discussion is to treat all effects that alter the *efficiency* of research inputs, whether human or inanimate, as operating through the second, indirect channel of "knowledge spillovers." The direct impacts, therefore, are to be understood as being restricted to those affecting supply and demand in the market for

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firm behavior...The motivations for government's involvement, however, has received little attention. When the issue has been extensively examined, it has typically been from a normative perspective and has not been intended to provide positive analysis of governmental motivations and the effect of those motivations on the form of R&D contracts." These remarks could be extended to apply also to the deficiencies of the economics literature on government funding of non-mission-oriented, basic research such as typically is conducted in academic institutions. Work in the "new economics of science" has been directed to repairing the latter defects. See, e.g., David and Dasgupta (1994), Stephan (1996), David, Foray and Steinmuller (1999).

[8] On tacit knowledge and its economic significance, see David, Cowan and Foray (1999), and works cited therein.

research resources of a constant "quality." But it should be equally apparent that influences flowing through the knowledge-spillover channels also impinge upon the determination of prices in the markets for research-inputs.

A further useful distinction may be drawn between government R&D outlays that, on the one hand, aim to procure research results germane to the presently defined missions of various public agencies, and, on the other hand, non-mission-oriented exploratory R&D of the sort that has come to be labeled (unsatisfactorily) as "basic research." The former we prefer to characterize as *contract R&D*, irrespective of whether it is performed for the agencies in question by private firms, or in government laboratories. Exploratory research, even though it might turn out to contribute to future mission capabilities in ways that currently are not clearly foreseen, also may be pursued under public sector management. In the US institutional context, however, this latter class of publicly supported research, which we designate for simplicity as *grant R&D*, has been carried on largely under "academic" auspices – whether in university research labs or on the "campuses" of national institutes. [9]

The third of our classificatory axes is one that distinguishes between those impacts that register more or less contemporaneously with the change in R&D expenditures, and those that ensue with some considerable lag. Following conventional short-hand usage, we consider the former within the framework of a single period "comparative statics" analysis; the label "dynamic effects" is reserved for the others. This allows for the possibility that whereas the immediate impacts of increased public sector R&D expenditures might be to "crowd out" private R&D investment, the longer run relationship between the two may be that of complements and not substitutes.

Introduction of these timing considerations raises the issue of evaluating the path integral of such effects; and that in turn, properly poses the question of whether (and with what discount rate) the expenditure streams of the two sectors ought to be cumulated and compared to determine whether the overall dynamic relationship is that of complements or substitutes. While one must take this preliminary notice of the matter, it is not one that can be resolved on this occasion.

The organization of the following sketch is straightforward: we begin with "static equilibrium" configurations, and under that heading proceed by considering, first, effects that take place via the research-input market, and then via knowledge spill-overs. Under the latter, we distinguish the between the impacts of different kinds of government R&D programs.

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[9] It may be remarked that the distinctions between defense and civilian R&D, and, within the latter category, between "basic" and "applied", although familiar from the U.S. National Science Board statistics, and mirrored in the data published by other nations, do not seem particularly useful for our immediate analytical purposes. Rather than emphasizing differences in the characteristics of the knowledge sought, either in terms of direct utility (commercial or military) or indirect utility ("basicness"), we prefer to direct attention to the institutional setting and contractual arrangements. These impinge differentially upon the scope for knowledge spillovers, and the nature of the research inputs that are used. See Dasgupta and David (1994) for further discussion.

1. Static Effects

Joint production conditions aside, the generic impacts of increased government R&D expenditures on company funded R&D that are likely to be felt most immediately are those channeled through the market for research inputs that are in inelastic supply. We can distinguish what may be called "first-order crowding out", from second-order effects:

1.1 The *static first-order effect* is simply the short-run impact on prices of research inputs, arising from the competition for these between the public and private sectors. The rise in prices is expected to translate into higher costs, since these are specialized inputs and the elasticity of substitution, and hence of demand for, say, researchers and engineers with particular expertise, will likely be low. The first-order effects are considered to be so short-run that the impact of the output from the public R&D expenditures is not an issue. Consequently, the expected effect of rising R&D performance costs is to reduce the expected rate of return on the private sector's investment, leading some projects to be curtailed – *ceteris paribus*. But while the scale of research efforts is reduced by the higher relative prices of research inputs, the impact upon the level of company expenditures remains ambiguous at this qualitative level of analysis.

1.2 *Second-order static effects* include the expected effects upon private sector rates of return owing to the knowledge that may be gained from the current R&D carried out in the public sector. Here there are potentialities for "crowding out" to occur in the following three ways:

(a) Firms may reallocate their R&D funding away from longer-term projects in the expectation that current public sector expenditures will provide results that they can eventually exploit for their future applied R&D.

(b) Firms may shift "applied" R&D away from projects where they anticipate that results of increase public research would become available to competitors, and so vitiate the commercial returns from product development in those areas.

(c) Contract R&D research performed with government funds displaces R&D that firms might have to do as part of the fixed costs of production for goods other than those demanded by the government. In other words, in a full-employment-like situation, government final demand crowds out private final demand, and takes out derived private R&D with it – precisely because the government is subsidizing the fixed R&D costs of the goods it wants.

But, it is also possible that complementarity would be observed because the anticipated consequences of current public expenditures stimulates concurrent private R&D outlays via the following two channels:

(d) Public R&D in a particular area may signal government intention to promote the use of a particular technology. Insofar as this may entail either a future commitment to demonstration and diffusion activities by public agencies, or favorable tax incentives for adoption of such technologies, the expected private rate of return on proprietary technological innovations in that field would be raised.[10]

(e) Admittedly, the effect noted in (d) is the "signal" of future demand. But, this is likely to be observationally equivalent to the impact of the expectation that public R&D will yield some infrastructure knowledge (to use Link's terminology) that will reduce private R&D costs, or decrease the variance of project costs. Insofar as there is a prospect of future "racing" for proprietary inventions in the field, there is an incentive for companies to start exploratory R&D projects in order to position themselves to take advantage of the knowledge "spillovers" from the public research. This possibility is nothing other than one of the "two faces of R&D" identified by Cohen and Levinthal (1989): doing R&D to create a capacity to absorb R&D results being generated elsewhere, should extend to absorbing public R&D results.

2. Dynamic Effects

The main points to be noticed under this heading concern the consequences of the lagged responses of input supply and knowledge spillovers from previous results of R&D performance with public funds. It is perhaps worth pointing out, as a preliminary remark, that dynamic complementarities may exist that differ in nature from the static effects of anticipations which were noticed above under (1: points d and e). Consider a stationary dynamic process, such as the steady-state equilibrium path envisaged in a growth model in which exogenous public and endogenous private R&D are rising *pari passus*. Even though complementarity effects of knowledge spillovers were not being anticipated but were being realized with a lag that induced the growth of R&D investment by firms, the growth in the two sectors would appear to be contemporaneous, and so indistinguishable from the "static" effects. This carries some immediate implications for econometric efforts to identify the impact of government R&D expenditures on private sector investment. One needs "shocks" in the form of a policy change, on one side or the other, to identify the underlying structure; and also a theory about the stability and speed of convergence to equilibrium.

(a) Given the long training periods for scientific and engineering personnel, it is more plausible to consider the impact of demand shifts upon wage rate (and or training incentives) as having a proper "dynamic" effect on the available supply of R&D workers.[11] In the absence of knowledge spillover effects, and with supply response

[10] Examples of this would include "alternative energy technologies," such as solar, and methanol fuel, both being areas of private R&D that were stimulated in the 1970's by public research (U.S. Department of Energy) in the field. Similarly, a major program of research to develop fluidized coal bed techniques for electricity power plants, was undertaken in the U.S. at the time by the Electric Power Research Institute (EPRI), an industry-supported non-profit organization.

[11] Under unusual conditions, such as mobilization for war-time emergencies, it is possible to shift scientists and engineers rapidly from corporate research labs to government military R&D programs. But, apart from

taking a stock adjustment form, the implication is that the greater elasticity of the long-run labor supply will simply moderate the impact on the wage rate, but it does not vitiate it completely. There would be a reduction in the quantity of labor engaged in company financed (private) R&D performance. Whether this translates into a rise or a fall in the private sector's level of real R&D expenditures will depend upon the magnitudes of the demand elasticities involved. (Formal modeling can address this question.)

(b) Adjustment processes that are far from smooth have characterized the market for scientists and engineers. Responses to demand shocks from government R&D, especially that driven by scaling up and scaling down of defense and non-defense mission agency programs (NASA Apollo program, Department of Energy Synfuels program, "Star Wars", etc.) have led to overshooting and volatility in the salaries of scientists and engineers in the relevant areas. Therefore, it should be recognized that either public or private R&D budget increases today, and the expectation of further expansions to come, can lead to pecuniary effects which may end up expanding the supply of research workers. That would reduce the real supply price to the other sector, once the demand in the initiating sector had returned to its long-term trend level. Even if the wage rate is not reduced below its initial level, the additional trained workers will add to private sector R&D performance for some long while; having been "sunk," their human capital investments do not disappear even though their income expectations are disappointed.

The econometric complication this introduces is that the lagged positive employment effect in the private sector is likely to coincide with the reduction of public sector employment, and, *a fortiori*, expenditures (as wage rates drop back to trend). So, in time series analysis, one may pick up the inverse short-run co-variation of public and private R&D and conclude that the substitution effects are dominant. That there is a ratchet-like positive association, reflected in the trend expansion of the public and private sectors, will be harder to identify from the aggregate data. Again, the point is that a structural model is essential to identify what is going on.

It is possible that there are dynamic, or long run crowding out effects too:

(c) The notion that government labs, firms and academic institutions, have specific research trajectories, and training effects, implies – in a nice "path dependent" way – that today's mix of public and private funding can shape the capacity (and relative costs) of tomorrow's research system. For example, more funding for

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that, the quantitatively important sources of short-run elasticity in the supply of trained research personnel for either sector would appear to involve international migration. Immigration policies, therefore, should be regarded – far more than is usually the case – as part of the institutionally determined parameters that influence the impact of national R&D policy. The mobility of research workers is well recognized as a significant consideration by current analyses of the role of the location of R&D expenditures on rates of innovation and the geography of industrial development. But the tradition of international trade theory encourages abstracting from the possibility of labor mobility, and has concentrated discussion of international R&D "spillover effects" exclusively upon those involving the transfer of knowledge without directly impacting the market for researchers.

academic research could result in training more researchers who sought to emulate their professors, and hence – if average quality remained constant – would be less immediately useful when employed on proprietary company R&D projects.[12] This is just the dynamic form of static competition for resources at the margin, except that the appropriate model is of the putty-clay sort: young twigs being "twisted" for life by the circumstances of their early environments. But, the nub of the problem would seem to be poor forecasts and the high fixed costs of switching curricula in a "timely" way, especially when this involves cutting old educational programs to make room for new ones.

(d) Still more esoteric possibilities may be contemplated.[13] Reduced funding of academic R&D can lead to increased real levels private sector R&D performance (and results) in the short-run, but, if salaries and research opportunities in the academy fall, the consequence may be some lowering of the quality of graduates who take up academic careers; and poorer quality training for the next generation of researchers. So, in the longer-run, the diminished flow of fundamental advances would tend to reduce the rate of return on private applied R&D. Were that to contract accordingly, the end result is the shrinkage of the total volume of expenditures on R&D. This is a example of cross-catalytic positive feedback: because the total budget for R&D is not fixed, the contraction in one sphere eventually yields a complementary effect in the other, even if in the interim the dominant effect is that of substitution between them. Obviously, with these hypothesized spirals movements in either direction – upwards or downwards – are possible, but their dynamics may not be symmetrical with respect to speed.

Our sketch-map has by now become sufficiently complicated with lines of influence that run in opposing directions that the most useful form of further annotation would be of the sort that attached relative measures of strength to the indicated forces. This is a job for explicit modeling.

IV. THE ANALYTICAL EXPLORER'S ANNOTATED GUIDE

By undertaking some formal modeling exercises we can hope to pass beyond mere identification of the various different channels of influence and the signing their likely effects, and arrive at an evaluation of the overall, *net* impacts upon private sector R&D expenditure level. In doing so one necessarily loses a good bit of the complexities and nuances that characterize the original problem. But there also are some compensating rewards: we can obtain insights into which of the system's parameters are especially crucial in determining when the overall impact would be the crowding out of private R&D by public R&D, and when the reverse (complementary) effect would dominate. Although the usefulness of having a structural model to aid in the interpretation of econometric results

[12] In the mid and late 1980's there was considerable complaint directed at university science and engineering departments in the U.S., on the ground that the kind of training they were providing was not suited to the needs of the private sector; and worse still, than an appreciable number among the graduates were perceived not to be employable in an academic sector whose research and teaching needs had ceased to expand.

[13] The dynamic example presented in compressed form in the following paragraph is based upon the more extensive discussion in Dasgupta & David (1994).

should hardly need to be restated, this topic-area is one where the marginal payoff from taking that advice seriously would still seem to be quite high.

1. A Simple One Period Model

This model is a highly simplified starting point for the analysis of the effects of public subsidies to R&D on private R&D performance. Such virtue as may be claimed for it will have to rest entirely on its heuristic value. Our formal analysis abstracts from 1) labor supply effects for R&D workers, which are assumed to be quite small in the short run due to the length of time necessary for training; 2) spillover effects from public R&D to private R&D, which are assumed to operate with a lag; 3) unemployment in the R&D sector (that is, we assume that the marginal product of R&D labor in the private sector justifies hiring the last worker in equilibrium – a simplification that seems plausible in a developed Western economy but less plausible elsewhere).

We define the following variables:

G	Public R&D budget ("exogenous")
L	Total labor supply of R&D workers (exogenous in the short run)
L_P	Number of private R&D workers (determined by the model)
L_G	Number of public R&D workers (determined by the model)
w	Wage rate of R&D workers (determined by the model)

The model has three equations:

$L = L_P + L_G$	The labor supply identity
$G = w\, L_G$	The government R&D budget
$w = f(L_P)$	The marginal product of labor

where $f(\cdot)$ is a *continuous monotonic* function such that $f'<0$ and $f''<0$ (i.e., there is a downward sloping derived demand schedule for R&D labor in the private sector).

These equations express the idea that the government budget determines the number of public R&D workers given the wage, the remaining workers go into the private sector, where the downward sloping marginal product function together with the number of workers actually determines the wage. From these 3 equations, one can compute the short run effects of an increase in the budget on the wage and the number of R&D workers in each sector. Combining the equations, we obtain:

$$f(L_P)\,(L - L_P) = G \quad .$$

Differentiating:

$$[f_L \cdot (L - L_P) - f(L_P)\,]\; dL_P = dG$$

or, more simply,

$$[f_L L_G - w]\, dL_P = dG$$

which implies that the number of private R&D workers always declines with an increase in the government budget (because $f_L<0$ and $w>0$). Obviously, the reverse is true for public R&D workers, due to the adding up constraint. It is easier to interpret the second version:

$$[-f_L \cdot (L_G) + f(L_P)]\, dL_G = [-f_L L_G + w]\, dL_G = dG$$

This says there are two effects. The second term is the direct effect on the government demand for R&D workers at a given wage. The first term is the effect due to the fact that (with a fixed labor supply) increased government funding increases the wage of R&D workers and therefore their required marginal product in the private sector. It is the latter that brings about the reduced quantity of research inputs (L_P) demanded by the private sector.

One can show explicitly that the wage rate must rise. Starting from the first-order condition for cost minimization in the production of innovations,

$$w = f(L-G/w)\ ,$$

total differentiation yields

$$dw = f_L \cdot (G\, dw / w^2 - dG/w) = (G/w - w/ f_L)^{-1} dG = f_L dG / (f_L L_G - w)\ .$$

This expression is easier to interpret when rearranged in elasticity form:

$$(G/w)\,(dw/dG) = f_L L_G / (f_L L_G - w) = 1/(1 - (L_P/L_G)(1/\varepsilon))\ ,$$

where $\varepsilon<0$ is the elasticity of the wage (marginal product) with respect to the number of private R&D workers. Therefore the elasticity of the wage with respect to government spending is bounded between zero and one. The first term in the denominator is just the direct effect on the wage, due to the larger budget being applied to the same number of R&D workers. The second term is the knock-on effect of a reduction in the number of private R&D workers due to the higher wage and therefore higher required marginal product. This mitigates the direct wage effect captured in the first term, because as the number of workers is reduced due to the supply constraint, it becomes easier to satisfy the marginal product condition necessary to clear the labor market for R&D workers.

To summarize, in this simple model with fixed R&D labor supply we readily can see that government funding of R&D must reduce the number of private R&D workers and increase their average wage. In order to determine whether the combined effect is higher or lower private R&D expenditure, we combine these results to obtain the elasticity of private R&D spending ($R=wL_P$) with respect to the government budget G:

$$\begin{aligned}(G/R)\, dR/dG &= L_G (dw/dG) + (wL_G/L_P)\,(dL_P/dG)\\ &= wL_G /(L_P\, (f_L L_G - w)) + f_L L_G (f_L L_G - w)\end{aligned}$$

$$= - (f_L L_G + wL_G / L_P)/(w - f_L L_G) = -(1+\varepsilon)/[(L_P/L_G) - \varepsilon]$$

The first term in this expression is due to the reduction in the number of private R&D workers from an increase in government spending and the second is due to the corresponding increase in the wage. The sign of the elasticity will be determined by the following condition (note that the denominator of the above expression is positive):

Private and public R&D are complements where $(-f_L) > w/L_P$ and $\varepsilon < -1$.

That is, in the region where the marginal product of R&D is elastic with respect to the number of workers, we should observed an increase in private R&D when the government budget increases if the supply of R&D workers is fixed.

The conclusion from this simple model is that *observed* private R&D spending will increase in response to an increase in government spending if the marginal product of private R&D is very responsive to a change in the number of workers. But, it will decrease if the marginal product of R&D is not very responsive. We might therefore expect that the former condition would hold when the relative size of the private R&D sector large; in this case the wage effect on the remaining workers dominates the reduction in the number of private workers, and spending on private R&D increases. This carries a quite useful message for econometric studies of macro-level relationships, whether in international cross-section or panel data: the observed relationships will not be uniform in direction if private sector R&D are preponderant in some economies, whereas public sector R&D dominates in others.

Thus, increases in government R&D expenditures unaccompanied by the expansion of the share of government *contract* R&D should be expected to result in an equilibrium increase in the level of company-financed R&D expenditures in settings where company-financed R&D is absorbing the greater portion of the nation’s research inputs. The latter condition might be indicated, say, by the predominance of the business sector’s share in total employment of Ph.D. scientists and engineers. Among the OECD countries, the relative share of the business sector in civilian R&D is larger where the manufacturing sector’s share in GDP is substantial, as it is in the US, Japan, and the major northern European countries. By contrast, among the comparatively lower per capita income countries having a less developed industrial base, public sector R&D is preponderant in the national total of R&D. The results of the foregoing highly simplified analysis suggest that it is among the latter economies that public sector R&D expenditures might well have substantial “crowding out” effects, contributing to keeping the overall R&D to GDP ratio at low levels in these lower income countries. This would be so even when public research expenditures did not take the form of contract procurement of R&D from domestic firms.

The foregoing results, as has just been noticed, abstract completely from the question of what sort of research is being funded in the government sector, and the bearing that this may have upon the generation of positive spill-overs to business firms. In the following sub-section we examine a slightly more realistic variation of the model that allows greater scope for such sources of complementarity effects, while maintaining the assumption that the number of R&D workers is fixed.

2. Infrastructure (basic) R&D versus applied (government contract) R&D

The first extension to our model considers the choice between government funding of basic (non-goal-oriented or infrastructure) research and government funding of applied research conducted in the private sector, given an overall level of government funding. This choice is a stylized representation of a policy question that has been important in some economies in recent years.[14] It implies that the government has at least two policy instruments at its disposal, the level of government funding G, and the fraction of that funding devoted to basic research, b.

We assume that the government assigns a share of researchers (c>0) to work in the private sector as applied R&D workers (e.g., in the defense industry, or via ATP funding) and that the remaining share (b=1-c) is employed in producing infrastructure knowledge (e.g., via the National Science Foundation or NIH). By assumption, the first group of workers is a perfect substitute for private R&D workers in the production function, so that the marginal product of R&D labor is now written $f[cL_G+L_P]$. The second group of R&D workers does not produce directly, but, because it expands the knowledge base available to applied R&D workers, the public researchers' output shifts the private sector's marginal product curve outwards. Therefore the total marginal product of R&D labor now takes the following form:

$$K[(1-c)\,L_G]\,f[cL_G+L_P] = K[b\,L_G]\,f[L-bL_G] = K[b(L-L_P)]\,f[(1-b)L+bL_P]$$

where K'>0 and K''<0 (K a positive concave function).

We can now ask again how the number of private workers will respond if the budget G is increased, and also how the choice between basic and applied R&D affects the desired level of private R&D spending and its marginal product. The first result is that complicating the model in this way does not alter the basic result that a higher government budget will increase the wage and reduce the demand for private R&D workers if their supply is fixed. But the channels through which this process takes place are somewhat more complex than before.

The marginal productivity condition in the private sector now yields the following equation:

$$K[b(L-L_P)]\,f[(1-b)L+bL_P]\,(L-L_P) = G$$

Differentiating, we have:

$$[(Kf'-K'f)\bullet b(L-L_P) - Kf\,]\,dL_P = -\,(ZbL_G + w)\,dL_P = dG$$

where Z is defined to be equal to (K′f - Kf′). Once again, every term in this expression is negative (under the assumption that the government budget is positive), so that the effect of an increase in R&D support is to reduce the number of private R&D workers in the economy.

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[14] See, e.g., National Academy of Sciences (1995), otherwise known as "The Press Report," as the committee responsible for it was chaired by Frank Press.

The second term is the direct wage effect from the government's demand for R&D workers, as before. But the first term now contains two effects: the reduction in demand for R&D workers due both to their increased wages (the Kf′ term), and to the fact that each worker is more productive because of the government infrastructure spending on R&D (the -K′f term).

The wage effect is also similar to the one derived in the previous section. A little manipulation shows that the elasticity of the R&D wage with respect to government spending is now given by the following:

$$(G/w)\,(dw/dG) = ZbL_G\,/(ZbL_G + w) = \varphi/(1+\varphi)\ ,$$

where we now define $\varphi = ZbL_G/w$ is the elasticity of the R&D marginal product with respect to the number of government workers, holding the total number of R&D workers constant. In this setting, shifting one worker from private R&D to public R&D has an unambiguously positive effect on the marginal product, because the private firm will move up the marginal product curve at the same time that it is being shifted out by government research. Therefore the elasticity of the wage with respect to government spending on research varies positively with the elasticity of the marginal product with respect to government-funded R&D workers.

The combined effect on total private R&D spending is the same as before:

$$(G/R)\,(dR/dG) = (ZbL_G - wL_G/L_P)/(ZbL_G + w) = [\varphi - (L_G/L_P)]/(1+\varphi).$$

Once again, private and public R&D spending are complements if φ is larger than the ratio of public to private R&D workers. In fact, it is easy to show that the elasticity of private R&D expenditure with respect to public is the sum of two simple expressions, one for the wage and one for the number of workers:

$$(G/R)\,(dR/dG) = [\varphi - (L_G/L_P)]/(1+\varphi) = \varphi/(1+\varphi) - (L_P/L_G)/(1+\varphi)$$

Clearly the first term is positive and the second negative. In addition, the magnitude of the response depends on the relative size of the private sector (it is large if the private sector is large relative to the public sector). Although the relationship to the marginal product elasticity is more intricate, it is still possible to show that private R&D elasticity with respect to government spending is increasing everywhere as φ increases (the marginal product of R&D with respect to public R&D workers becomes less elastic) – at least in the case where we hold the number of workers in each sector constant. That is to say, if we compare two different economies with the same or similar L_P/L_G ratios, for the one where φ is large, private and public R&D are complements; but, as φ decreases towards zero, they become substitutes.

Thus, the effects of total government spending on private R&D in this model are the same as that in the previous model (although their magnitudes may be different). This is a simple consequence of the fact that the infrastructure effect on the marginal product of private R&D has the same sign as the direct effect due to the R&D worker supply constraint ($L = L_P + L_G$).

A more interesting exercise is to examine the effects of a shift toward applied R&D in the government budget: to accomplish this we hold the budget G fixed and differentiate with respect to b, the share of public R&D workers engaged in basic research:

$$-[(Kf'-K'f)\bullet(L- L_P)^2]\, db \;+ [(Kf'-K'f)\bullet b(L- L_P) - Kf\,]\, dL_P = 0$$

This equation yields the result that increasing the basic research share unambiguously increases the number of private R&D workers, holding the government budget and the total number of R&D workers constant:

$$dL_P/db = (L- L_P) \,/\, \{b + Kf/ [(L-L_P)\,(K'f-Kf')]\} = L_G \,/b\{1 + w/ZbL_G\} > 0\ .$$

Or, in elasticity form,

$$(b/L_P)\, dL_P/db = \varphi\, (L_G/L_P)/[\, 1+ \varphi] \;> 0$$

Thus the elasticity of private R&D employment with respect to the share of public R&D devoted to infrastructure research is proportional to the relative size of the two sectors; and it varies positively with the elasticity of the R&D marginal product with respect to the number of government workers. If infrastructure investment is very productive, or the private marginal product curve is steep, or the government share is large, the number of private R&D workers will increase sharply in response to an increase in b. What that means is this: the more responsive is the private marginal product of R&D to the spillovers arising from government *grant-type* R&D funding, the bigger the increase in the number of private R&D workers that we can expect in response to an increase in this share. If the private marginal product of R&D is unresponsive to such funding, then shifting government workers from applied R&D to basic research has no effect on the private sector.

The wage effect also is positive, which is rather to be expected:

$$dw/db = ZL_G \,/(1 + ZbL_G \,/w) = \varphi(w/b)/(1+ \varphi)$$

which implies an elasticity of

$$(b/w)\, dw/db = \varphi/(1+ \varphi)>0\ ,$$

identical to the elasticity with respect to government spending.

Therefore, the total effect on private R&D spending of increasing the share of public R&D spent on “infrastructure research” is unambiguously positive:

$$(b/R)\,(dR/db) = \varphi\, (L_G/L_P)/(1 + \varphi) \;+ \varphi/(1 + \varphi)=$$

$$= \varphi(L/L_P)/(1 + \varphi)\ .$$

We can summarize our results thus far in tabular form, as follows:

Table 1
Short-run Response of Private R&D

Policy Instrument	**Effect (elasticity)**		
Variable	# Private R&D Workers (L_P)	R&D wage (w)	Private R&D Expenditure (R)
Total government R&D budget	Negative $-(L_G/L_P) / [1 + \varphi]$	Positive $\varphi/[1 + \varphi]$	Positive if $\varphi > L_G/L_P$ $[\varphi - (L_G/L_P)] / [1 + \varphi]$
Share of Basic Research	Positive $[(L_G/L_P)\,\varphi] / [1 + \varphi]$	Positive $\varphi/[1 + \varphi]$	Positive $[\varphi\,(L/L_P)] / [1 + \varphi]$

In regard to the impact of expanding government R&D that takes the "non-contract" form, our findings accord with the thrust of most of the recent economics literature that argues the theoretical case for government support of non-commercially oriented civilian R&D.[15] They are in accord also with the analysis and econometric results of several studies that have been carried out at much lower levels of aggregation. The work of Leyden and Link (1992) on the impacts upon U.S. industry R&D of NIST's programs of infrastructure technology research in the areas of optical fibre standards, and electromigration characterization, could be cited as illustrative in this connection. Another clear instance is provided by Toole's (1997, 1999) detailed studies, which reveal complementarities between NIH-funding of research and pharmaceutical company R&D investments in specific categories of drugs.

These, and still other technologically specific studies,[16] somewhat paradoxically may be seen to conform more closely than would broader industry-level analyses to the foregoing model's strong assumption with regard to the inelasticity of the relevant supply of labor. At least in the short and medium terms, by carrying out empirical studies that control tightly the scientific and engineering area, one can more closely approximate the situation in which the aggregate labor supply cannot undergo marked adjustments.

To get at the conditions that are relevant in the intermediate levels of aggregation, and *a fortiori*, to longer-run macro-level relationships, it is necessary to further elaborate our simple model by allowing for some real wage elasticity in the aggregate supply of researcher workers. The general intuition of doing so is clear enough, for this would tend to mitigate the impact of increased R&D budgets, whether public or private, upon the price of research inputs. But, as we have seen thus far, much of the interest, and the surprises, dwell in the modeling details, to which we must accordingly turn.

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[15] See, e.g., David (1997, 1998) and Klette, Moen and Griliches (1998) for recent surveys.

[16] Much of the evidence of a detailed kind is not econometric, but remains instructive nonetheless. See, e.g., National Research Council/ Computer Sciences and Telecommunications Board (1999) on the role of government funded research programs in the information technology revolution.

3. Allowing for an Elastic Labor Supply

As was indicated earlier, sustained increases in either government or private spending on R&D that induce higher wages for scientists and engineers are likely eventually to lead to increases in the labor supply of these types of workers. This takes place through two channels: induced immigration of scientific and technical personnel, and an increase in domestic university-leavers who are qualified to take up R&D employments. Thus, in the medium or long-term we do expect to see a labor supply response to increased demand for R&D that will mitigate some of the positive wage and spending effects shown in Table 1. To analyze the magnitude and channels for these effects, we can enrich our model by the addition of a simple labor supply equation:

$L = L_P + L_G$	The labor supply identity
$G = w\, L_G$	The government R&D budget
$w = K[bL_G]\, f[(1-b)L_G+L_P]$	The marginal product of labor
$g(w) = L$	The labor supply equation

Before examining the solutions of this model it will be convenient to summarize our expanded notation, which is presented in Table 2. The key new parameter is η, which is the labor supply elasticity, assumed to be positive; in the previous section, this parameter was set equal to zero.

Table 2
Notation and Definitions

Symbol	Description	Sign	Definition
ε	SR private labor demand elasticity (no b).	<0	$F_L L_P$ /w
φ	Marginal product elasticity with respect to L_G holding L constant.	>0	b(K'f-Kf') L_G/w = bZ L_G/w
η	Labor supply elasticity (long-run).	>0	g´(w) w/L
ψ	Labor demand (marginal product) elasticity with respect to L holding L_G constant.	<0	Kf´L/w
Γ	Denominator in Table 2. (total indirect effect on private labor).	>0	$1-\eta\psi+\varphi$

Table 3 presents the results of solving this model. Note first that the denominator of all the elasticities is larger, so the elasticities themselves will be smaller in absolute value, other things equal. The new term is the product of the long-run labor supply elasticity (positive) and the direct marginal product elasticity holding the supply of government workers constant (negative). As more R&D workers enter the market, they reduce the responsiveness of both the wage and the demand for private R&D workers by a factor proportional to the marginal product of those workers.

Table 3
Long-run Response of Private R&D

Policy Instrument	**Effect (elasticity)**		
Variable	# Private R&D Workers (L_P)	R&D wage (w)	Private R&D Expenditure (R)
Total government R&D budget	Positive if $\eta\varphi L > (1-\eta\psi) L_G$ $[-(L_G/L_P)(1-\eta\psi) + \eta\varphi(L/L_P)]/\Gamma$	Positive φ/Γ	Positive if $\varphi(\eta L + L_P) > (1-\eta\psi) L_G$ $[-(L_G/L_P)(1-\eta\psi) + \varphi(1+\eta L/L_P)]/\Gamma$
Share of Basic Research	Positive $[(L_G/L_P)+\eta (L/L_P)] \varphi / \Gamma$	Positive φ/Γ	Positive $[\varphi (1+\eta)(L/L_P)] / \Gamma$

The most important result in this table is that the unambiguously negative elasticity of private R&D workers with respect to government spending now depends on a variety of elasticities and on the size of the government sector:

$$(G/L_P)\, dL_P/dG \;\Leftrightarrow \eta\varphi \;/\; (1\text{-}\eta\psi) > L_G/L \;.$$

Thus, *real* private R&D spending is more likely to *increase* in response to an increase in nominal government spending when the government R&D sector is small, when the labor supply elasticity is large, when the government workers have a large effect on private productivity, or when the marginal product curve is flat (small ψ). In this case, the response is magnified by the positive wage effect, and nominal private R&D spending also increases.

In contrast, real private R&D spending will *decrease* in response to an increase in nominal government spending when the government sector is large in relative terms, when the labor supply elasticity is small, when government R&D does not enhance private productivity, or when the marginal product curve is steep. As in the inelastic labor supply case, the response of nominal private R&D spending to an increase in government spending can go either way. The condition for a positive nominal R&D response in this case is

$$(G/R)\, dR/dG \;\Leftrightarrow [\eta\varphi \;/\; (1\text{-}\eta\psi)]\, [1 + L_P/\eta L] \;> L_G/L$$

A second major result in this table is that the elasticity of private R&D spending with respect to the infrastructure share, whether nominal or real, is likely to be larger than the elasticity in Table 1. The condition for this to happen (for nominal R&D) is the following:

$$(1\text{-}\eta\psi+\varphi)/(1+\eta) > \text{-}\psi$$

As long as the marginal product curve is fairly flat, this condition is likely to hold.

4. Summary of model results

We conclude this section by summarizing the main results of our simple model. We analyzed the short and long run effects on real and nominal private R&D spending of two possible changes to government R&D policy: an increase in overall spending and an increase in the share devoted to basic “infrastructure” research. In general, the long run impacts are more benign than the short run, primarily because the long run allows the supply of scientists and engineers to adjust to increased demand for their services, whereas in the short run, the effect of increased government demand in the face of inelastic S&E labor supply is to drive up wages in that sector.

For our first policy experiment (an increase in the total public R&D budget), we find that real private R&D decreases in the short run, but will increase in the long run if the government R&D sector is relatively high, the labor supply of scientists and engineers is elastic, or the marginal product-R&D curve is relatively flat (that is, effect of R&D on productivity does not fall very quickly as R&D budgets increase). Nominal R&D will increase in the short or long run, except when the public share of total R&D is very large.

For our second policy experiment (an increase in the share of public R&D devoted to basic research), we find the rather simple result that both real and nominal R&D will increase in both the short and the long run, with the effect larger in the long run. This result is due to the fact that increasing the share of basic research *holding the total public budget constant* increases the private productivity of R&D without the attendant negative effects via the demand for R&D workers.

IV. SOME QUANTITATIVE THOUGHT-EXPERIMENTS

In this, penultimate section it is appropriate to undertake a preliminary assessment of the empirical plausibility of our framework and its implications for "crowding out." Our approach will be to combine the theoretical results summarized in Tables 1 and 3 with elasticity estimates for some key parameters, drawing upon the econometric findings of others for the latter.

The questions of greatest immediate interest pertain to the probable magnitudes implied for the other, unknown parameters of the model, and the consequent signs of the elasticity of nominal and real private R&D spending with respect to increases in public R&D spending. Recall that those magnitudes are in question only for the case we describe as "the long-run," because in the "short run" the labor supply is taken to be fixed and the real volume of R&D resources invested (the number of R&D workers) has been shown to necessarily decrease when government expenditures rise. It should be evident that the computations reported here are rather conjectural in character; they are primarily illustrative in purpose, but offer a "reality check" on our model.

Our first avenue of exploration exploits the very interesting estimates that have been obtained by Austan Goolsbee (1998) for the short and medium to long-run elasticity of the R&D-worker wage with respect to R&D spending. Using a panel of scientists and engineers drawn from the U.S. Current Population Survey for the period 1968-1994, Goolsbee estimates that short-run wage elasticity for these workers with respect to nominal federal R&D spending is equal to 0.22, with a standard error of 0.03.[17] Although he does not report a long-run wage elasticity, he does obtain an income response to the average of the past four years of R&D that is 0.13 below the short-run income response. From this we will infer that the medium to long-run wage elasticity is approximately 0.10.

Turning to Table 1, we can immediately use this information to calculate an estimate of φ, the elasticity of the private marginal product of R&D with respect to government workers L_G, holding the total labor supply constant:

$$\varphi = 1/((1/.22)-1) \cong 0.28$$

Thus, we may say that in the short-run, at least for countries similar to the United States, the measured nominal private R&D response to an increase in public spending will be

[17] Although it is unclear from the published paper, the numbers reported in Table 1 of the paper are actually elasticities rather than regression coefficients for the level variables as the table seems to indicate (Goolsbee, private communication, 1998). We are interpreting this as the elasticity with respect to nominal spending because the R&D figures he uses are not adjusted using an actual R&D deflator, although they are adjusted (implicitly) by the GDP deflator.

positive if the government share is less than about 0.22.[18] If the short-run wage effect were similar in other developed countries, we would expect that countries with larger government shares would display crowding out behavior. This is consistent with the results in Guellec and van Pottelsberghe (1999), who find that countries with high subsidization rates have negative public R&D coefficients in the private R&D investment equation. However, the latter results are based on error-corrected regressions, which deliver long-run rather than short-run behavior. It is also not clear from Guellec and van Pottelsberghe's paper whether the subsidization measure upon which their analysis focuses really corresponds closely to the measure of public support adopted here – which encompasses all government R&D spending. Reassuring as the reported results are, they have to be taken with a grain of salt.

In the case of the United States, the government-financed share of R&D spending fell from about 60 percent to 36 percent over the course of the period examined by Goolsbee (1998). That would imply both that the *short-run* impact of any increase in public funding – without a shift in the mix favoring grant support – should have been to crowd out private R&D, but that this impact should have weakened appreciably between the late 1960's and the mid-1990's. This result is moderately consistent with the trends of reported magnitudes surveyed in David, Hall and Toole (1999), although many of the results pertaining to the U.S. imply complementarity rather than crowding out.

Turning to the long-run response of private R&D, Goolsbee's estimate of 0.10 for the wage elasticity has the following implication:

$$0.10 = \varphi/\Gamma = \varphi/(1-\eta\psi+\varphi) = 0.28/(1.28-\eta\psi) \Leftrightarrow \eta\psi = -1.52$$

We can use this result to bound the long-run elasticity of real and nominal R&D with respect to an increase in government R&D spending. For real spending, the elasticity is

$$\begin{aligned} \partial \log L_P/\partial \log G &= [-(L_G/L_P)(1-\eta\psi) + \eta\varphi(L/L_P)]/\Gamma \\ &\cong [-2.52\,(L_G/L_P) + 0.28\,\eta\,(1+L_G/L_P)]/2.8 > 0 \\ &\Leftrightarrow \eta > 9\,(L_G/L) \end{aligned}$$

This has two implications: first, the long-run labor supply elasticity of R&D workers needs to be quite large for the real effect to be positive, unless the government share is very small. Second, as the government share of spending rises, it becomes more likely that crowding out would be observed even in the long run.

The elasticity of nominal R&D expenditures, however, is slightly larger than the magnitude just considered (because it includes the positive wage effect, equal to 0.10). The condition for this elasticity to be positive is therefore given by:

$$\begin{aligned} &[-(L_G/L_P)(1-\eta\psi) + \varphi(1+\eta L/L_P)]/\Gamma > 0 \\ &\Leftrightarrow [-0.9\,(L_G/L_P) + 0.10\,(1+\eta\,(1+L_G/L_P))] > 0 \end{aligned}$$

[18] The short-run elasticity of private R&D with respect to public R&D is positive if $\varphi > L_G/L_P$, or if $\varphi/(1+\varphi) > L_G/L$.

$$\Leftrightarrow \eta > 9\,(L_G\,/L) - 1$$

which is slightly easier to satisfy. For a country such a Japan, in which the government share of R&D funding was below one-fifth at the beginning of the 1990's, the critical value of the long-run labor supply elasticity would be something like $\eta > 0.8$. It is not implausible, then, that there would have been little crowding out effects from the major program of expanded public funding for science that was called for by the Council for Science and Technology in Japan in 1996 and approved by the government of the day. In view of the thrust of that program towards changing the mix of national R&D expenditures strongly in favor of university-based, "grant" research, it would seem that the plan was particularly well-calculated to yield a long-term positive stimulus to private sector R&D.[19] But, as this particular example underscores, to have arrived at the right science and technology policy is not the same thing as having the public sector resources with which to implement it. As a result, one of the less serious consequences of the difficulties that have beset the Japanese economy in recent years has been to deprive us of an interesting natural experiment with which to test the empirical implications of our model.

V. CONCLUSION

We begin with a cautionary reminder: the model presented here, although it captures the key public R&D impacts, is highly stylized and results may differ if a more complex setting is analyzed. The primary problem is the heterogeneity of R&D, both public and private, which makes it difficult to talk about moving down a single marginal product curve. For example, we distinguished only two kinds of public R&D spending, basic and other, one of which enhances private productivity while the other does not. In reality, the situation is most countries is much more complex, ranging from defense R&D through various applied R&D programs for energy and the environment through budgets for basic science and higher education.

We also assumed that R&D spending consisted only of the wages of scientific personnel, whereas in fact, although this is the major portion of R&D budgets, they also include spending on equipment and supplies. This is unlikely to have a major impact on our results, because the "production function" for R&D tends to include a fixed amount of such spending per R&D employee; it will however moderate any precise magnitudes that we have computed. Finally, we assumed constant elasticity production functions and supply functions throughout. Where our results are unambiguously signed, they would not change under different functional forms (as long as the signs of the elasticities remain unchanged). However, some of our conditional statements and magnitudes might be modified if constant elasticities did not hold.

Turning to our main substantive conclusions, many OECD economies have increased or are contemplating increasing the public support of R&D over the past decade or so. What we have shown in this paper is that an important ingredient in the assessment of the effects of these increases is the issue of the flexibility of scientific labor supply in

[19] See, e.g., the report in the *International Herald Tribune*, 25 June, 1996, p. 1.

response to increases in its wage. Although this topic is an old one, it usually goes under the heading of "manpower planning" and is often treated as a branch of the labor economics literature that is separate from the R&D and technology policy literature (see, for example, Arrow and Capron 1959, Lerner 1992, or Stephan 1996). Our first proud conclusion from the analysis above is that the time has come to integrate the understanding and results from this literature into the study of R&D investment decisions. That is, at least when doing policy analysis at the economy-wide level, it is not appropriate to treat the private R&D-doing sector as price and wage-taking and to focus attention only on the dollar amount of R&D spending. In this, we are to a certain extent echoing and reinforcing a point made by Goolsbee (1998).

Where we have the appropriate numbers available, the implications of our simple model are not inconsistent with observed behavior. Our second general conclusion, therefore, is that is this type of analysis would appear to be worth pursuing in future international comparative research, using more precise data on the cross-country variations in the relative size of the public and private sectors, subsidy rates, wage rates for R&D workers, and R&D cost variables. Some greater attention to structural specification has been seen to be quite feasible as a complement to econometric estimation. Indeed, it offers a way to make greater sense of the variety of empirically observed responses of private R&D to public R&D expenditures, and represents our best hope of being able ultimately to identify the various channels through which those emerge.

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