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Is public R&D a complement or substitute for private R&D? A review of the econometric evidence

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Abstract

Is public R&D spending complementary and thus ''additional'' to private R&D spending, or does it substitute for and tend to ''crowd out'' private R&D? Conflicting answers are given to this question. We survey the body of available econometric evidence accumulated over the past 35 years. A framework for analysis of the problem is developed to help organize and summarize the findings of econometric studies based on time series and cross-section data from various levels of aggregation (laboratory, firm, industry, country). The findings overall are ambivalent and the existing literature as a whole is subject to the criticism that the nature of the ''experiment(s)'' that the investigators envisage is not adequately specified. We conclude by offering suggestions for improving future empirical research on this issue. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The opening of the new millennium finds a national public-sector civilian research enterprise whose scale and scope in most of the world's countries surpasses that of any previous period of their history. Among the leading industrial nations this may be seen as the outcome of a long historical process initiated with state patronage during the scientific revolution of the seventeenth century. But, only since the closing decades of the nineteenth century have organized research and development activities begun to make appreciable claims upon the productive resources of those societies. [2] Since then, however, the fraction of real gross national product being directed by both private and governmental agencies toward expanding the base of scientific and technological knowledge for non-defense purposes has trended up-

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[2] See, e.g., David (1998a; b), Lenoir (1998), and sources cited therein.

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wards — halting at times, yet never reversing significantly.

Most of the growth in the relative importance of this intangible form of capital accumulation has come within the past half-century: even under the stimulus of military preparations during the 1930s, total R&D expenditures in countries such as the US, the UK and Japan remained in the range between two-thirds and one-quarter of one percentage point of their respective national product figures. [3] In the aftermath of World War II, the belief that organized research and development could stimulate economic growth and contribute to improving economic welfare led to the creation of many new public institutions supporting civilian science and engineering, and pushed the civil R&D fraction upwards towards the one percentage point level in a growing number of countries. The Cold War Era fostered a further expansion of government agency research programs in non-defense as well as military technologies, and established models for the performance of government-funded R&D by private sector contractors. Thus, accompanying the institutional expansion in public sector production of scientific and technological knowledge, there were enormous increases in the scale of public financial obligations for R&D activities performed primarily by non-governmental agents. Added to these, a variety of tax and subsidy measures was introduced with the intention of encouraging private firms to undertake R&D projects at their own expense. [4]

Although most people believe that government R&D activities contribute to innovation and productivity, many economists and policymakers have grown frustrated with the paucity of systematic statistical evidence documenting a direct contribution from public R&D. The burden of econometric findings concerning the productivity growth effects of R&D seems to be that there is a significantly positive and relatively high rate of return to R&D investments at both the private and social levels. Yet, quite generally, privately funded R&D in manufacturing industries is found to yield a substantial premium over the rates of return from ''own productivity improvements'' derived from R&D performed with government funding. [5] In a recent survey, Griliches (1995, p. 82), suggests that the especially pronounced differential over the returns on tangible capital investments observed at the private level may reflect individual firms' perceptions of especially high private risk in the case of R&D. The latter would, of course, lead to the imposition of higher hurdle rates of return for firms' individual funding decisions; whereas, by comparison, government-funded industrial R&D projects would be seen as carrying less (private) risk, especially as much of it is devoted to ''product innovation'' for ''output'' that eventually is to be sold back to the government procurement agency under the terms of ''cost plus'' contracts. In such circumstances there is little basis for expecting that the R&D it performed with public monies would have a substantial direct impact on the contracting firm's own productivity.

1.1. The issue: substitution *vs.* complementarity in public and private R&D investments

Having a direct impact on innovation that shows up as industrial productivity growth, however, is not the only way in which public R&D may enhance

[3] See the estimates in Edgerton (1996), Table 5.8, but note that the R&D fraction shown for Japan (as 0.22% of national income in 1934) actually refers to share of GNP and is based on the results of a 1930 survey; a Japanese survey taken in 1942 returned expenditures on the order of 1.5% of GNP. See Odagiri and Goto (1993), p. 84.

[4] For an historical account focusing upon the US in the twentieth century, see Mowery and Rosenberg (1989) and the contributions dealing with particular sectors and industries in Nelson (1982). For the post-Cold War climate affecting government support, especially in the US, see Cohen and Noll (1997). Nelson (1993) brings together profiles of the evolution of the 'national innovation systems' of a variety of industrialized and some developing countries, mainly since the 1960s; Soligen (1994) provides a broader, internationally comparative treatment of relations between scientific research and the twentieth century state.

[5] See Griliches (1995) and Hall (1996) for recent surveys. Negative findings on the productivity growth payoff from government expenditures for industrial R&D emerged from an earlier econometric studies by Griliches (1980), Griliches and Lichtenberg (1984), Bartelsman (1990) and Lichtenberg and Siegel (1991), some of which obtained coefficients on federally funded R&D that were close to zero as well as statistically insignificant.

economic performance. Public funding of R&D can contribute indirectly, by complementing and hence stimulating private R&D expenditures, even if it has been undertaken with other purposes in view. Government agencies sponsor some research and development projects and programs because the knowledge gained is expected to be germane to their respective mission capabilities, as often is the case, for example, in areas such as military technology and logistics, and public health. This kind of R&D work sometimes will be assigned to the staffs of public institutes and national laboratories, although it equally may be procured through government contracts with R&D-performing firms in the private sector. [6] Beyond its putative direct value as an input into the provision of government-provided services, both the defense-related and civilian R&D expenditures funded through public agencies may generate social benefits, in the form of knowledge and training ''spillovers.'' These often are held to enhance private sector productive capabilities, and, specifically, to encourage applied R&D investments by firms that lead to technological innovations — from which will flow future streams of producer and consumer surpluses. [7]

The theoretical plausibility of such claims notwithstanding, available empirical evidence on the issue remains rather short of being conclusive, to say the least. Economists, continuing in the tradition pioneered by the research of Blank and Stigler (1957), recurrently examine a variety of data for signs as to whether the relationship between public and private R&D investments is on balance characterized by ''complementarity,'' or by ''substitution.'' Several recent econometric studies, for example, document positive, statistically significant ''spillover'' effects via the stimulation of private R&D investment by publicly funded additions to the stock of scientific knowledge. [8] The same might be said regarding a considerably more extensive body of historical case studies, detailing the influence of government-sponsored research programs and projects on commercial technological innovation. [9] Many among the latter studies, however, focus on US federally funded research performed in academic institutions or quasi-academic public institutes, and so do not bear immediately on the questions raised concerning the impacts of publicly sponsored R&D conducted under contract by industrial corporations. Nor do they inform us about the effects of publicly funded mission-oriented commercial research in the rest of the world. Moreover, while some studies in this area have been able to support claims of positive spillovers from public to private expenditures, there is no shortage of investigations that arrive at the contrary conclusion. Thus, it is found that some public R&D contracts actually have done little or nothing to promote the efficient functioning of the government agencies involved, and yet also failed to provide significant commercial ''spillovers.'' In still other instances, the benefits that private companies derived from the public R&D expenditures are said to have been both predictable and large enough to have elicited financing by profit-seeking firms, had the political process not invoked subsidization of those projects at the tax-payers' expense. [10] Wherever publicly funded R&D is seen to be simply substitut-

[6] For example, the 1996/1997 data compiled by Stoneman (1999, Tables 1 and 6) show that the UK government funded 31.8% of total (military and civil) R&D, somewhat less than half of which (14.4% of total R&D) was performed in government departments and laboratories run by the Research Councils. From the National Science Board (1998, Appendix Table 4-3) figures for the US in 1996, the corresponding (federal and non-federal) government shares in funding and performance are seen to be 32.5% and 8.9%, respectively. By adding to the latter figure the 3.3% of federal government-funded R&D that was performed in non-profit federally funded research and development centers (analogous to the research units of the UK Research Councils), we arrive at 12.2% for the overall share of total R&D that was performed in US government research facilities. The latter, like the US governmental share in total R&D funding, rather closely resembles the contemporary situation prevailing in the UK.

[7] See, for example, the recent formulation of the economic case for public support of research, in National Research Council (1999), especially Chaps. 1–2, with historical case studies drawn from the US federal government's role in the development of computing and communications technologies.

[8] That, at least, is the inferential interpretation of the results reported by Jaffe (1989), Adams (1990), Acs et al. (1991) and Toole (1999a; b). See further discussion in Section 3.4.

[9] Among recent, sophisticated contributions to this literature, see Link and Scott (1998) and National Research Council (1999).

[10] See, e.g., the examination of Cohen and Noll (1991) of a selection of large-scale mission-oriented commercial R&D programs that were funded by the US federal government.

ing for, or actually ''crowding-out'' private R&D investment, it obviously is hard to justify such expenditures on the grounds that they exerted an immediate net positive impact upon industrial innovation and productivity growth. [11]

Simply counting up the numbers of findings pro and con that have accumulated on the issue of public–private R&D complementarity since the mid-1960s, however, cannot be very informative. Our approach instead will be to survey the available body of econometric work systematically, and in some detail, from an analytical perspective. Although we take notice of a number of time-series studies that have been carried out at the macroeconomic level, most of this inquest is concerned with research that focuses on the impact of public R&D contracts and grants upon private R&D investment by manufacturing firms and industries. It is there that the bulk of R&D expenditures by the world's developed economies continues to be concentrated. Our purpose in this is to assess the reliability of the statistical findings and to arrive at a better understanding of the reasons for the persisting lack of a clear-cut empirical consensus in the literature.

Three quite restricted questions will be asked regarding those investigations. First, is the design of the statistical analysis such that it can yield any reliable findings on the question of whether government R&D expenditures do or do not have a significant and economically palpable impact upon their private sector counterparts? Secondly, where the findings are credible, may we conclude that government subsidy programs do not displace private R&D investment, but instead have the complementary effect of inducing additional company-funded R&D activities? Thirdly, how can the econometric findings be reconciled with those of other well-designed studies that addressed ostensibly the same question, yet arrived at different conclusions?

At this time, the econometric results obtained from careful studies at both the micro- and macro-levels tend to be running in favor of findings of *complementarity* between public and private R&D investments. But, that reading is simply an unweighted summary based upon some 30 diverse studies; it is not a conclusion derived from a formal statistical ''meta-analysis,'' and in no sense is it offered here as a judgement that would pretend to settle the issue definitively. To formally weigh up and aggregate the available (and still-growing array of statistical analyses) seems to us a virtually impossible task in this case. We are not dealing with statistical results that have been generated by properly designed ''experiments'', where provision was made in the policy process for replication and ''controls.'' Instead, we are dealing with ex-post inquiries, and the results reported by many of the individual papers that constitute the literature on this topic reflect a convolution of many counterbalancing effects that are further compounded with the effects of a varying mix of public funding and other incentives for R&D activities. The ability of the econometricians to impose ex-post statistical controls varies widely among these studies. Moreover, they are distributed over differing time periods, and across a variety of scientific and technological fields, as well as diverse sectors and different economies.

Inasmuch as the spheres of investigation as well as the findings considered here are far from uniform, it is difficult to see what good would be served by striving for a broad empirical generalization that might mask clear-cut instances, however few, where publicly funded R&D is found substantially to displace private investment. Indeed, the better way of proceeding would seem to lie in trying more precisely to identify and delineate the characteristics of the circumstances in which ''substitution'' effects predominate. Policy making in this area of growing long-term importance calls for more specific empirical support and guidance if it is to advance beyond general theoretical arguments, intuitive practical judgements, and political rhetoric.

1.2. Cautions regarding the survey's scope and limitations

It should be made explicit at the outset that the present review is addressed to only one aspect of the

[11] It remains conceivable, however, that some special features of the government-sponsored projects create capabilities in the performing firms that are conducive in the longer run to increased private R&D investment, to higher marginal innovation yields, or to both.

broader empirical picture that is of interest for public policy formation. For one thing, we do not examine the large body of evidence on the relative productivity impacts of public and private R&D. [12] A second issue that we do not treat in any detail is the other side of the interdependence of public and private R&D spending, namely, the latter's impact upon the former. Many of the micro-level empirical studies we have surveyed treat public R&D either explicitly or implicitly as an exogenous influence on private R&D within an investment framework. Consequently, in a number of instances we do find it necessary to point out the econometric consequences of ignoring the existence of latent variables that may jointly effect both public- and private-sector decisions to allocate R&D funding to specific industrial areas, and to have the work performed by particular (rather than randomly drawn) firms. Our discussion recurrently touches on this point, arguing that more attention to structural modeling of government agency behavior as well as industrial R&D responses is needed for a proper interpretation of the overall, reduced-form findings. [13] This may be seen as an instance of the more general case that David and Hall (1999) advance for taking an explicit structural modeling approach to mitigate the frequency of apparent contradictions and ambiguities in the econometric literature.

1.3. Organization

The remaining presentation is organized as follows. Section 2 presents a conceptual framework for understanding the net effects of public R&D upon private R&D investment activities. Section 3 reviews and critiques the available econometric research findings, beginning with studies carried out using data for the line-of-business and laboratory level (Section 3.1), and progressing upwards to those concerned with effects at the level of the firm (Section 3.2), the industry (Section 3.3) and the aggregate economy (Section 3.4). Because the bulk of the economic research on this question looks at publicly funded R&D that is being performed under the terms of government contracts with commercial firms, the main focus of discussion in this survey falls upon programs of that kind. In Section 3.5, however, notice is taken also of a small body of econometric studies that examine the impacts on private R&D of publicly funded/publicly performed research or publicly funded/non-profit performed research. [14] We conclude in Section 4 with several methodological observations and suggestions for future research in this area of perennial policy relevance.

2. ''Net'' private R&D effects of public R&D: a conceptual framework

Before proceeding further, it is appropriate to pause to ask what modern ''technology policy measures'' have been meant to achieve. Presumably the central rationale for government support of R&D is the correction of the market failures in the production of scientific and technological knowledge, arising from the ''incomplete private appropriability'' problems identified by Nelson (1959) and Arrow (1962). Economists have indicated two main policy responses to the resulting tendency towards underprovision of knowledge-based innovative effort on the part of profit-seeking business entities: direct procurement and/or production in public facilities, and incentives for a greater amount of private investment. We have here eschewed issues concerning the first of these, primarily those involving the performance of public research institutes and national labo-

[12] More recent work on this question is surveyed by Klette et al. (2000).

[13] The studies by Leyden and Link (1991) and Leyden et al. (1989) are noticed as having set a good example for future work in this regard.

[14] Recent studies by Jaffe and Trajtenberg (1996) and Jaffe et al. (1998) use patent citations to investigate the flow of knowledge and commercial technology out of federal labs, but our discussion is restricted to papers that explicitly deal with the impacts upon private R&D investment.

ratories, and have restricted our review exclusively to the second class of policy responses.

2.1. Tax incentives vs. direct subsidies for R&D

Under that heading two main policy instruments may be identified: tax incentives that reduce the cost of R&D, and direct subsidies that raise the private marginal rate of return (MRR) on investment in such activities. Although not strictly necessary, the primary difference in execution between these two policy instruments is that the former typically allows the private firms to choose projects, whereas the latter usually is accompanied by a government directed project choice, either because the government spends the funds directly or because the funds are distributed via grants to firms for specific projects or research areas.

The effectiveness of R&D tax credits in increasing R&D in private firms is surveyed in Hall and van Reenen (1999, this issue). Because a tax credit directly reduces the marginal cost of R&D, one would not expect to see ''crowding out'' effects on industrial R&D, spending except via the channel of an increase in the real cost of R&D (if the inputs are in inelastic supply). This implies that crowding out of nominal private-sector R&D expenditures would not be observed, even though it is entirely possible that there could be displacement of private real R&D investment if the prices of the inputs increased sufficiently.[15] Tax credits, however, do not leave the composition of R&D unaffected. As firms expand their R&D activity in response to linked tax offsets against earnings, the incentives are likely to favor projects that will generate greater profits in the short-run. Consequently, projects with high social rates of return, and long-run exploratory projects and ''research infrastructure'' investments in particular, may be less favored by the expansion of private funding. In this way, rather weaker ''spillover'' benefits to other firms and industries would be generated by the private response to extensive reliance upon this particular pro-R&D policy instrument.

By contrast, direct funding of R&D programs designated by government agencies allows public R&D subsidies to be targeted toward projects that are perceived to offer high marginal social rates of return to investments in knowledge. At least in principle, such funding could be concentrated in areas where there was a large gap between the social and the private rate of return. For this reason, direct R&D subsidies or government spending on basic research activities should not be expected to displace private real R&D investment, except via its generic impacts on the price of research and development inputs that are in inelastic supply. Yet, the possibility remains that in the politics of technology policy formation, there will be strong pressures to provide subsidies for projects with high private marginal rates of return — possibly to assure the appearance of successful public ''launch aid'', or simply because the prospective private payoffs make lobbying for subsidies an attractive undertaking. In such circumstances, it is more likely that increased direct government funding for industrial R&D projects would enable firms correspondingly to reduce their own outlays. This form of ''investment displacement'' arises primarily because R&D activities are heterogeneous rather than homogeneous, and it is distinguishable from, and additional to the form of ''crowding out'' identified by David and Hall (1999) as operating through the R&D input market effects of public expenditures.

2.2. The need for a structural framework

When considered as a whole, the literature under review here may be characterized as predominantly inductive in its approach to considering the effects of government R&D funding upon the level of business R&D investment behavior. That is not simply to say that the orientation of this work has been primarily empirical rather than analytical, but, rather than the empirical approach pursued is essentially descriptive in nature, aiming at establishing the sign and magnitude of the overall or ''net'' effect in question. Few studies in this area have been espe-

[15] See David and Hall (1999) for a full discussion of the impact of inelastic R&D inputs on the effects of R&D subsidies.

cially concerned to delineate the different channels of influence that may connect R&D resource allocation in the two spheres, and fewer still attempt structural estimation in order to ascertain the character and strength of the underlying effects associated with each such channel.

Although all these empirical studies acknowledge being motivated by the same over-arching policy issue, the widespread tendency to eschew explicit structural modeling has reinforced the common failing of econometric work in this field to specify adequately what ‘‘experiment’’ the investigators implicitly envisage conducting. In other words, supposing one could vary government policy, what observed pairings of policy action(s) and sequelae would establish whether public and private R&D were ‘‘complements’’ or ‘‘substitutes?’’ Taken together with the fact that a large number of very different empirical ‘‘experiments’’ at various levels of aggregation are contemplated (in effect) by the research literature, this lack of specification contributes to the difficulties of interpreting the individual findings and reconciling the seeming contradictions among them.

For the foregoing reasons, rather than out of any methodological precommitment to favor structural modeling approaches in econometric analysis, we believe it will be best to review the evidence presented by the individual studies only after having set out a general conceptual framework that identifies the array of hypothesized micro-level determinants of private sector R&D investment, and relates these in turn to relationships that hold and manifest themselves at the macro-level. That is our task in the present section.

2.3. Determinants of private R&D investment at the micro-level

A useful framework for understanding how public R&D affects R&D funding decisions in the private sector is provided by an adaptation of a familiar, rather elementary model of firm-level investment behavior. To our knowledge, such a framework was first employed for this purpose by Howe and McFetridge (1976). It postulates that, at each point in time (or for each planning period), an array of potential R&D investment projects is available. [16] The firm is assumed to rationally consider the expected cost and benefit streams for each project, in order to calculate its expected rate of return. Under certain conditions, these can be thought of as internal rates of return and therefore used by the firm in question to rank the associated projects in descending order of anticipated yield, thereby forming its MRR schedule.

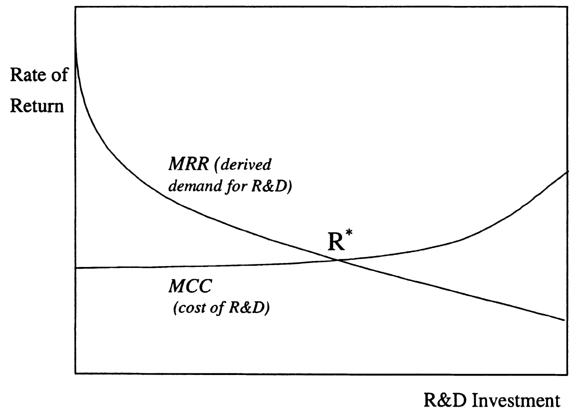

Fig. 1.

A downward-sloping schedule of this kind appears in Fig. 1, where the marginal yield (and the marginal cost of capital) is plotted on the vertical axis, and the horizontal axis gives the cumulated amount of investment required as one proceeds down the list of projects. (Following expositional convention, each project is implicitly taken as being finely divisible, so that the resulting MRR schedule is continuous and continuously differentiable). Under

[16] This formulation abstracts from important issues concerning the determinants of the firm’s access to the scientific and engineering knowledge base that is relevant for formulating plausibly feasible R&D projects, and estimating the time distribution of the costs and benefits of the innovations they would generate. There is a well-known recursion problem here, inasmuch as among the research projects that a rational decision process would need to consider is the project for gaining the knowledge required to construct and evaluate its current ‘‘innovation possibility set’’. But, in a full dynamic specification, it is straightforward analytically to treat the latter as a lagged endogeneous variable.

this construction, as one moves along a given schedule describing the distribution of projects in the firm's prevailing ''technological innovation possibility set,'' there is no alteration in the constellation of other variables that would influence the rates of return on the array of R&D projects in the firm's potential portfolio. The net impact of any and all alternations in those other conditions, therefore, must show up as shifts in the MRR schedule.

As also may be seen from Fig. 1, the firm faces a marginal cost of capital (MCC) schedule, which reflects the opportunity cost of investment funds at different levels of R&D investment. [17] The upward slope of this schedule over its full range is attributable to the fact that as the volume of R&D investment is increased the firm will have to move from financing projects with internally generated funds (i.e., retained earnings) to calling upon external (equity and debt) funding. Use of retained earnings for R&D accounts for the flat range at the left of the MCC schedule, whereas the firm's increased recourse to external financing would tend to push its marginal costs of capital upwards. [18]

It should be apparent that as the MCC schedule in Fig. 1 describes the opportunity cost of capital, it would slope upwards eventually. This must be so even were it the case that all of the firm's R&D investment remained financed out of retained earnings; at the margin, expansion of the R&D investment budget would force the firm to turn to external financing for its tangible capital acquisition projects.

The foregoing simplified schema can be represented by the following equations:

$$\mathrm{MRR} = f(R, \boldsymbol{X}), \tag{1}$$

$$\mathrm{MCC} = g(R, \boldsymbol{Z}), \tag{2}$$

where R is the level of R&D expenditure, and $\boldsymbol{X}$ and $\boldsymbol{Z}$ are vectors of other ''shift variables'' that determine the distribution of project rates of return and the associated marginal costs of capital, respectively. The X-variables reflect:

(i) The ''technological opportunities'' governing the ease with which it is possible to generate innovations (relevant to the firm's market area);

(ii) The state of demand in its potential market area or line-of-business;

(iii) Institutional and other conditions affecting the ''appropriability'' of innovation benefits.

Correspondingly, the Z-variables include:

(i) Technology Policy measures that affect the private cost of R&D projects (such as the tax treatment of that class of investment, R&D subsidies, and cost-sharing programs of government procurement agencies);

(ii) Macroeconomic conditions and expectations affecting the internal cost of funds, via the general state of price-earnings ratios in equity markets;

(iii) Bond market conditions affecting the external cost of funds;

(iv) The availability and terms of venture-capital finance, as influenced by institutional conditions (such as the development of IPO markets) and the tax treatment of capital gains.

As is depicted by Fig. 1, in the firm's profit maximizing equilibrium the optimal level of R&D investment is found at R^*, where the MRR and the marginal cost of funds are equalized:

$$R^* = h(\boldsymbol{X}, \boldsymbol{Z}). \tag{3}$$

Several points are now obvious about the relationship between private R&D investment and public

[17] This implicitly holds constant the amount of other, tangible capital formation expenditures that the firm has scheduled for the planning period in question. Although the assumption of risk neutrality on the part of the firm is implied by the use of the expected MRR as a sufficient statistic to describe each project in the portfolio, it should be recognized that in practical capital-budgeting exercises firms add premia to their marginal costs of capital, forming ''hurdle rates of return'' that allow for the riskiness of various classes of investment. Although, for expositional simplicity it has been supposed that the tangible capital formation budget has been predetermined, at the margin R&D should compete with all other capital projects on the basis of their risk-adjusted internal rates of return.

[18] Obviously, in the case of R&D intensive ''start-ups'' there are no retained earnings upon which to draw. But, the possibility exists of borrowing capital from employees by paying them with stock option, which may keep the marginal cost of capital down so long as there is an adequate supply of qualified personnel who also happen to have a high tolerance for risk, although issuance of stock options does have a cost due to its effect in diluting equity.

R&D funding. First, if we take the provision of public funds to be exogenous, the effects of such ‘‘shocks’’ would show up as a shift of either the firm’s MRR schedule or its MCC schedule, or of both. For example, direct R&D subsidies, and cost-sharing arrangements by public agencies, by relieving the firm of some joint costs of research and development activities would be tantamount to shifting the position of its MCC schedule to the right. Had the firm initially been facing increasing marginal costs of capital, this change would permit the undertaking of additional projects with its own money — other things being equal, of course.[19] To cite another specific illustration, the award of government R&D contracts to a small firm also might have the effect of lowering the recipient’s capital costs at the margin; especially in the case of start-up enterprises, where this could act as a signal for external funding sources to apply a smaller risk premium when setting their lending terms.

A number of other potential positive micro-level effects of government contracts for industrially performed R&D, also have been noticed in the literature following Blank and Stigler (1957). Each of the following three factors would appear as an outward shift of the MRR schedule in Fig. 1.

(a) Publicly subsidized R&D activity can yield learning and training effects that acquaint the enterprise with the latest advances in scientific and engineering knowledge, and so enhance its efficiency in conducting its own R&D programs.

(b) Where public funds are made available for construction of test facilities and the acquisition of durable research equipment, and also pay the fixed costs of assembling specialized research teams, the firm involved may be able to conduct further R&D projects of its own at lower (incremental) cost, and thereby derive higher expected internal rates of return on its R&D investments.

(c) Government contract R&D, by signaling future public sector product demand, and private sector demand in markets for dual-use goods and services, may raise the expected marginal rates of return on product or process innovation targeted to those markets.

There is a distinct possibility that in the case of the above-mentioned effects (a) and (c), the technological knowledge and market information associated with publicly funded R&D performed by one firm could result in ‘‘spillovers.’’ The latter would, similarly, raise the expected marginal rates of return for other firms in the same industry, and also for firms in other industries. Public R&D performed in academic and other non-profit institutions, including government laboratories, also could have correspondingly positive spillover effects. This is so particularly where the research resulted in the development of ‘‘infrastructural knowledge’’ — general principles, research tools and techniques, and skill acquisition that raised the expected rates of return on commercially oriented, applied R&D projects.[20]

2.4. Distinguishing between government R&D contracts and grants

When considering the potential ‘‘net’’ effects of public R&D activities, it is likely to be important to distinguish between public contracts and grants. Government R&D contracts in most instances are financial outlays to procure research results that are expected to assist the public agency in better defining and fulfilling its mission objectives. Such contracts are the largest component of public awards made to private for-profit firms, and also include all arrangements to purchase R&D- intensive public goods. This category covers much of the public aerospace and defense expenditure. Public grants, on the other hand, are usually competitive financial awards that do not carry any future public commitment to purchase. They are the primary mechanism

[19] It should be obvious, however, that were the firm facing a completely inelastic MCC constraint, the public contract funding would not have any positive incremental impact upon the level of company-funded R&D.

[20] Leyden and Link (1991) and David et al. (1992) suggest a variety of ‘‘spillover’’ channels through which the infrastructure-forming aspects of so-called ‘‘basic’’ research funded — and in some cases performed — in the public sector has a complementary impact upon private sector R&D investment.

for funding exploratory research for the advancement of knowledge and fostering emerging technologies.

Since the path-breaking work of Blank and Stigler (1957), four channels have been identified in the literature through which public contracts for industrially performed R&D could stimulate ''complementary'' private R&D expenditures in the short run:

(i) Public R&D contracts increase the efficiency of the firm's R&D by lowering common cost or increasing ''absorptive capacity;''

(ii) Public R&D contracts signal future demand;

(iii) Public R&D contracts may improve the chances for success on the firm's other projects;

(iv) Public R&D contracts allow firms to overcome fixed R&D startup costs — ''pump-priming.''

These imply that public subsidies either shift the firm's marginal returns schedule (in Fig. 1) out to the right, and/or that the firm's opportunity cost of capital schedule is shifted to the right, thereby eventually lowering the firms' MCC for the higher levels of R&D expenditure. The first three of the foregoing putative effects would shift the firm's MRR schedule rightwards either by increasing the expected revenues or decreasing the expected costs of the firm's available projects. The fourth effect, by decreasing a firm's fixed costs, lowers the opportunity cost of capital and shifts this curve out to the right. All of these ''complementarity effects'' suggest that public R&D contracts stimulate additional private R&D investment.

From the preceding discussion, it might appear that the micro-level impact on private R&D investment of both government contracts for industrial R&D and grants awarded to non-profit organizations would be unambiguously positive. But, there are two sorts of countervailing influences, both of which are likely to operate more strongly in the case of contracts. First, the performance of contract-specified lines of R&D with public funding may simply substitute for some (if not all) of the investment that the performing firms otherwise would have been prepared to undertake in order to be in a position to bid successfully for related government procurement contracts.

Secondly, publicly funded R&D also may militate against private sector investments in the same technological areas, because the expected rates of return to investments by firms that do not receive contracts tend to be lowered by the prospect that government contractors would succeed in producing commercially exploitable innovations. Doing so could leave them well positioned to enter the final product market with significant first-mover advantages. Non-contract receivers also might be discouraged from undertaking their own R&D by the anticipation that the government procurement agency in question would have an incentive to disseminate cost-saving and quality-enhancing innovations, as a means of enabling entry and greater competition in the end-product market. When viewed from the latter perspective, ''dual-use'' programs of government procurement of R&D-intensive goods take on the appearance of a two-edged sword. [21]

Both the direct and the indirect ''displacement'' effects just considered may be conceptualized as altering the shape of the firms' respective MRR schedules, reducing expected marginal returns on R&D projects belonging to particular technological areas that were ''targeted'' for public contract support. Although it is clear in principle that the policy prescription should be for the government to select projects for subsidization that the private sector is not likely to undertake, or not undertake in sufficient volume, matters may be otherwise in actual practice. Pressures within public agencies for high ''success rates'' in contract awards may lead to the use in R&D funding decisions of selection criteria that put heavy weight on factors that are correlated positively with high expected rates of return to private R&D funding. Therefore, when investigating the net effects of government-funded R&D at the micro-level, it is important to distinguish between programs that

[21] Government procurement costs may be reduced by taking advantage of spillovers from industry-funded R&D directed towards civilian products. But the potential for the R&D performed under cost-plus procurement contracts to have spillover effects on company financed R&D might, correspondingly, be nullified by the heightened anticipation of competitive entry into the business of exploiting dual-use designs. Such opportunities may exist where new high-tech systems required by government have components, or utilize methods applicable to the production of goods for private purchasers. On the benefits of dual-use technology programs, see Branscomb and Parker (1993).

provide grant funding and those that involve contracts. Likewise, when dealing with questions concerning aggregate level effects of changes in policies affecting public R&D, one should make allowance for the effects of any significant alterations in the distribution of funding between those two modes.

Although government grants typically do not have a final product demand-increasing component (such as is frequently present in the case of public contracts for R&D performance), they may cause the MRR schedule to be shifted upwards nonetheless. This would occur because a program of grant-funded research had raised firms' R&D efficiency, or had improved the risk-return pattern on other projects. The convention in the literature, however, has been to abstract from the ways in which these effects of grant-type funding for industrial R&D would impinge upon the shape or position of firms' MRR schedules, and so to identify whatever effects ensue as produced by shifts in the MCC schedule.

Three main analytical cases have been delineated. In the first, it is assumed that the firm is asset-constrained and thus faces a perfectly inelastic (vertical) MCC schedule at its current level of R&D investment. The award of a subsidy in the form of a public grant then shifts the MCC curve to the right, increasing the firm's performance of R&D by just the full amount of the subsidy. The second case postulates that the public grant shifts an upward sloping MCC curve to the right, so that the amount of the incremental increase in the amount of R&D the firm undertakes increases by less than the grant award. The third case considers that the MCC schedule is perfectly elastic (horizontal) at the pre-grant equilibrium, but is shifted downwards because the signal to equity holders provided by the public grant award lowers the firm's internal cost of funds. The magnitude of the increase in private R&D investment will then depend on both the strength of the ''signal'', which is likely to vary directly with the relative size of the grant, and on the slope of the firm's MRR schedule. Other things being equal, the ''flatter'' is the MRR schedule, the greater will be the increase in the induced amount of private R&D investment.

Thus, only the last of these speculative situations envisages the possibility of a complementarity effect of public grants for industrial R&D, i.e., one that would elicit *additional* private R&D expenditures. Grants to firms for R&D are likely to be used in ways that assure greater private appropriability of the benefits than is the norm for grant-funded research in academic institutions, and similar non-profit research institutes. There consequently may be justification for having presumed, in the foregoing analysis, that contracts yield no positive spillover effects that would induce significantly increased private R&D investment. But, by the same token, the same presumption should not be extended to considerations of the impact of all public sector grant funding.

2.5. Short-run ''net'' impacts on private R&D: from micro- to macro-level effects

In general, the likely direction of net effects of public R&D contracts on private R&D investment remains ambiguous. The previous discussion has reviewed an array of channels at the micro-level through which public contracts as well as grants would have positive effects on the level of privately funded R&D activity. On the other side of the ledger, however, two principal arguments have been advanced on behalf of supposing that public expenditures for industrial R&D would exert a ''crowding out'' effect on private R&D investment. The first of these is simply the micro-level displacement of funding, previously discussed. This would occur where contracts are targeted in areas of technological development that firms otherwise would still find it worthwhile undertaking; the resulting alteration in the shape of the MRR schedule may be such as to push it downwards and to the left.

The second argument introduces macro-level considerations. There is likely to be upward pressure on the prices of R&D inputs when the provision of funding to a particular firm or group of firms occurs in the context of an expanded government R&D program that absorbs substantial scientific and engineering personnel, along with other specialized materials and facilities. The resulting increased costs associated with the array of potential private R&D projects implies a lowering of the MRR schedule; and, other things being unchanged, that translates into a reduced level of business R&D investment.

Where will the balance be struck between the opposing forces arising from increased public sector R&D expenditures at higher levels of aggregation

— i.e., in technologically related industry groups, and the economy as a whole? [22] This question recently has been examined analytically by David and Hall (1999). Their basic proposition is simple: whenever the market supply of R&D inputs is less than infinitely elastic, as is likely to be the case in the short-run, increased public sector demands for those resources must displace private R&D spending, unless it gives rise to ''spillovers'' that also raise the aggregate private derived demand for R&D inputs. In the simple two-sector model developed by David and Hall (1999), the nature of the macro-level relationship between private and public R&D investment depends upon four parameters of the system. Complementarity, rather than substitution effects are likely to dominate where the relative size of the public sector in total R&D input use is smaller, where the elasticity of the labor supply of qualified R&D personnel is higher, where the grant–contract mix of public outlays for R&D performance is skewed more towards the former, and where the rate at which the private marginal yield of R&D decreases more gradually with increased R&D expenditures.

Without having fully specified both the magnitudes of the elasticities, and the shifts in schedules due to spillover effects, in an analogous manner for the microeconomic framework depicted by Fig. 1, the foregoing review of the static qualitative arguments for and against complementarity leaves one unable to determine the sign of the net impact of public subsidies on the level of business R&D expenditures. The general point that the foregoing discussion does bring out clearly, however, is the presence of identification problems due to the fact that the MRR and MCC curves may be shifting simultaneously. This must be dealt with if econometric studies are to succeed either in providing reliable estimates for the critical underlying elasticity parameters, or in simply ascertaining the sign of the net effect of public R&D contracts. It has been pointed out that both fixed costs associated with R&D startup, and resource constraint effects on input prices that are correlated with individual firms' receipts of funding, may be shifting the MCC schedule. By holding those effects essentially constant by the use of an appropriate econometric specification, including proper instrumental variables, it should be possible to evaluate the net impact of public R&D contracts on private R&D investment demand. The identified effect would measure the net movement of the firm's MRR schedule, holding fixed the opportunity cost of capital.

2.6. *''Dynamic'' or long-run effects of R&D subsidies*

Even though most of the empirical literature has been devoted to quantifying these presumed short-run (''static'') effects, we should recognize at least two ''dynamic'' or long-run effects that are partially the outcome of public R&D funding. First, informational spillovers from the advance of public science and engineering knowledge, much of which is made possible by government R&D activities, will likely shift the firm's MRR schedule outward over time. Since new knowledge is the main source of new technological opportunities, the outward shift of the MRR *curve* assumes that these opportunities take the form of higher project returns. Of course, such effects would be felt with variable lags and are likely to be localized among some subset of the underlying projects. So, the relevant schedules would undergo changes in shape as well as position and the impacts will not necessarily be felt symmetrically throughout the population of firms.

[22] Attention should be called to the analytical difficulty of passing explicitly from the micro-level framework of the previous subsections to the macro-level. In principle it would be possible to construct an aggregate private marginal efficiency of R&D investment schedule, from the union of all the projects (each with their individually perceived expected internal rates of return). As that might well involve duplicative investments in some projects, it should be evident that the private expectations would generally not be realized. The *consistent* aggregate private marginal efficiency of investment schedule would be lower, even with spillovers it is likely to lie below the aggregate *social* marginal efficiency of investment schedule. But the real difficulty lies in passing from the aggregate private MRR schedule to the aggregate demand for R&D investment when firms are realistically heterogeneous. The distribution of projects is not identical across firms, and neither do they all face the same MCC schedule. This means that there is nothing to guarantee that the same ranking of all the projects would be selected by a central profit-maximizing agent charged with allocating the private sector's total R&D funding.

A second dynamic effect stems from the training of new scientists and engineers. There is a strong and important emphasis in the US and UK public research enterprise on training, particularly within the research universities. Due to the trend toward increasingly heavy reliance upon foreign graduate students as research assistants on grant-funded academic research projects, one must not simply presume the existence of tight coupling between training activities and the future availability of qualified research personnel in the labor markets where such training occurred. But, insofar as there is a lagged input supply response from expanded public funding of R&D (grants), this could show up at the microeconomic level as an outward drift of the MRR schedule over time.[23] But, if one considers the situation in the market for industrial R&D personnel, it is more natural to conceptualize the aggregate effect in terms of a downward shift of the labor supply schedule. The latter would thus be a factor mitigating such demand-driven upward pressures on real unit costs of R&D that were set in motion by the expansion of government funding. In general, then, the balance of the long-run dynamic effects seems to favor the emergence at higher levels of aggregation of net complementarities, rather than a relationship dominated by ''crowding out'', or the substitution of public for private R&D investment.

2.7. Endogeneity, and common latent variables effects

Using this simple investment framework to clarify the expected channels of influence helps to formulate and evaluate the empirical ''tests'' that exist in the literature. It does not, however, allow us to address the possible mutual interdependence of public and private R&D expenditures. This may present an issue for econometric analysis, either because of simultaneity and selection bias in the funding process, or because there are omitted latent variables that are correlated with both the public and private R&D investment decisions. Endogeneity due to selection biases in R&D grants and subsidized loans to small and medium size firms has been addressed recently in the work of Busom (1999) and Wallsten (1999), whereas the possibility of omitted time-constant firm effects in the awarding of government R&D contracts was pointed out many years ago by Lichtenberg (1984). Lichtenberg also remarked on the problem presented by the fact that firms undertake a significant amount of preparatory R&D in order to qualify for government contracts and grants: this may create a situation in which the firm's MRR schedule already has shifted outward in anticipation of a public R&D contract or grant, and consequently the firm's response to the award may be more difficult to detect in the data.

More generally, it may well be that there are strong selectivity biases that lead firms which have a recognized competence for certain kinds of R&D to receive public contracts as well as to fund such activities with their own money. Beyond that, in cross-section analyses at the industry level, a distinct but related econometric problem may arise where both private and public investment decisions are responding to the same latent variable, namely, the inter-industry variation in the ''technological opportunity set.'' The possibility of exogenous changes in the state of the opportunities created for commercially attractive innovation — such as those opened up by developments in fiber optics, high-temperature superconductivity, or the availability of restriction enzyme techniques for ''gene-splicing'' — may confound efforts to identify the causal impact of public R&D allocations upon the pattern of private investment.

Even though the framework presented here has not undertaken to formalize these and other, more ''politically implicated'' sources of endogeneity in public R&D expenditures, it has assisted us in underscoring the need for empirical studies to be ex-

[23] On the economic significance of the rising numerical importance of foreign graduate students and post-doctoral fellows in university research systems, see Dasgupta and David (1994). There is substantial evidence, most of it accumulated from surveys of company executives responsible for research and development, that firms actively search for recent trainees of university departments that have successfully drawn public funding for basic research; that they regard recent graduates as an important source of practical knowledge about the use of new techniques. See, e.g., Levin et al. (1987) and Pavitt (1991). It remains unclear to what extent this public goods spillover effect via researcher training is equally characteristic of university-based research supported by industry funds, and conducted under restrictions typical of proprietary R&D.

plicit about their identifying assumptions, and to include proper ''control'' variables. The foregoing discussion also has highlighted the point that public R&D contracts are likely to have a much stronger immediate effect on the firm's marginal returns schedule than is the case with public R&D grants. For that reason alone, public contracts are more difficult to evaluate because those effects are readily confounded with the many other factors that shift the MRR schedule, including the nature of changes in the production and product technology, appropriability conditions, the type of product market competition, and so on.

As the previous discussion of identification problems may have suggested, to undertake to estimate the magnitude of the effect of public R&D spending upon private R&D investment at different levels of aggregation is tantamount to conducting rather widely differing ''experiments'' in the hope of determining ''the'' response. Some considerable doubt must surround the very idea that there is a universal relationship of that kind, and so it will be better to avoid casual comparisons and juxtapositions of findings, striving to compare like with like where that is feasible. Macro-level time-series studies have to consider feedback effects operating through price movement in the markets for R&D inputs, whereas in micro-level analyses the findings should reflect ''real'' rather than nominal expenditure relationships between public and private R&D. At least that would be so once controls had been entered for time effects (in the form of year dummies). Of course, in saying this we assume that there is substantial potential mobility on the part of R&D personnel among firms and industries. In other words, when ''the experiment'' under analysis involves the provision of a subsidy for R&D conducted by a particular firm, it is reasonable to assume that the firm faces a highly elastic supply of R&D inputs, and therefore that input prices and unit costs cannot be materially affected by the subsidy. [24] The implication is that the observed effect on the level of private R&D spending should be somewhat weaker at the microeconomic level than that found by studies conducted using aggregate data (since the effects in the former case are real rather than nominal).

Nevertheless, at the lower level of aggregation there are likely to be additional complications due to the presence of significant cross-sectional differences in technological opportunity or innovation capabilities (''competences'' in the terminology preferred by the recent management literature). Some controls for ''fixed effects'' may be appropriate in such cases. But, in studies based on firm- and industry-level panel data, over time the ''innovation opportunity sets'' may be undergoing differential alterations among the various technological and market areas. Simple, fixed effects methods are then likely to prove inadequate to the task, and more complex econometric tactics would seem to be called for.

Thus alerted to the numerous underlying complexities that beset those in search of a straightforward empirical answer to the question of whether ''complementarity'' or ''substitution'' prevails in this domain, we may now be in a position to critically examine the econometric findings which the literature presently has to offer.

3. The empirical literature: review and critique

Our survey is organized in subsections, distinguishing among the econometric studies according to their choice of the unit of observation, and by the type of data analyzed. Four types of observational units have been studied: line-of-business or laboratory, firm, industry, and national (or domestic) economy. The typical econometric approach is to regress some measure of private R&D on the government R&D, along with some other ''control'' variables. When a positive coefficient on the public R&D variable is found, this is interpreted as revealing the predominance of complementarity between public and private investments. On the flip-side, a negative coefficient is taken to imply that public R&D and private R&D are substitutes. In several studies, the authors use the magnitude of the estimate to make statements to the effect that ''a one dollar increase in public R&D funding leads to an X dollar increase

[24] This is precisely true only for the log–log specification, where the aggregate price effects are in the constant term, or when the number of firms receiving subsidies is a small fraction of the total so that there is no price effect in the cross-section.

(decrease) in private R&D investment.'' On the whole, however, the magnitudes of the published estimates are very diverse. [25] In some instances, they are very difficult to compare directly, owing to variations in the specification of the estimated equation, and the absence of collateral statistical information needed to calculate dimension-free parameter estimates, such as elasticities. Our summary tables present the estimated elasticity of private R&D with respect to public R&D wherever it has been possible to obtain this magnitude.

To achieve appropriate comparability among the findings, we divide the studies into four main groups, according to the nature of the statistical observations used and the econometric approach complied with the following.

(1) Pure cross-section studies at the micro level, where firms or industries with different levels of government R&D funding are compared. Here it is crucial to control for differences in demand conditions, technological opportunity, and appropriability.

(2) Panel data studies at the micro level within a given industry, in which there are controls for time-invariant differences among firms — each firm in effect serving as its own control, so that the results reflect individual firms' time-series responses to changes in government funding.

(3) Aggregate or macroeconomic studies, where the response is identified by changes in private R&D funding over time as a function of government R&D funding. Here it is important to control for macroeconomic influences that may be driving both variables. In addition, it is likely that results based on these studies will contain R&D input supply effects of the sort that are identified by Goolsbee (1998) and David and Hall (1999).

(4) Studies, whether micro or macro, that attempt to control for the simultaneity between private and public R&D spending using instrumental variables. It is probable that the results from these studies will differ from those in the other studies if common omitted variables are a problem.

The discussion in Section 2 urges caution when interpreting the results of some of these regression studies. For example, when we look across firms or industries in a cross-section, we are seeing a set of equilibrium choices for the level of R&D (R^* in Fig. 1), rather than tracing out the derived demand curve for R&D as a function of the position of the MCC curve. In fact, each of the firms and industries in question is likely to face a different demand curve for R&D investment, as well as a different MCC schedule. In addition, some of the effects of the public support for R&D will be to shift or otherwise change that curve. Many, but not all, researchers have attempted to control for the variability in the MRR curve when estimating the relationship, and in what follows we will try to assess the success of the approaches that they have taken in doing so.

Blank and Stigler (1957) suggested in their original formulation of the question that the most efficient and direct way to test for a complementary or substitution relationship is to analyze a sample of research programs over time within a ''suitable'' sample of companies. Due to data limitations, however, they were forced to rely on a cross-section of manufacturing firms in their analysis. Their method was to compare the ratios of scientific workers to all employment for firms with and without government contracts. For a total sample of 1564 firms in 1951, they found that firms with public contracts also had lower scientific personnel intensity working on private research. This result supports ''substitution,'' at least in the sense that public contracts were associated with fewer research personnel on private projects. When Blank and Stigler changed the sampling universe, however, and took it to be US manufacturing firms engaged in any R&D, public and/or private, they reported that ''in general substitution is now almost absent.'' [26] Finally, using their most reliable data for firms with more than 5000 employees, they found evidence for complementarity. These results are consistent with the view that although many individual firms may find it attractive to sub-

[25] For example, Wallsten (1999) concludes that there is a one-for-one crowding-out of private investment, whereas Robson (1993) concludes that there is a one-for-one stimulus of private R&D investment. To be sure, these studies were not analyzing the same dataset.

[26] Blank and Stigler (1957), p. 61.

stitute government funding for their own R&D budgets, the large firms are better able to take advantage of complementarities, due to knowledge spillovers and pump-priming effects. The latter may operate across lines-of-business and even standard industrial classification lines, so that the size of those firms may really be a surrogate for the product diversification that enables them to appropriate benefits from the less predictable range of their R&D projects. Blank and Stigler, however, warned that their estimate based on variation across firms and industries at a point in time could be seriously biased by other sources of heterogeneity, for example, variations in technological conditions faced by different firms.

3.1. Line of business and laboratory studies

The subsequent research of Scott (1984) and Leyden et al. (1989); Leyden and Link (1991), together with very recent work using Norwegian data by Klette and Moen (1998), are the only studies that follow the recommendation of Blank and Stigler (1957) to look ''below'' the firm level. For each of these studies, Table 1 lists the sample used, the econometric methodology and type of data, the form of the private R&D variable to be explained, the form of the public R&D explanatory variable, as well as the ''net'' findings reported by the authors.

Scott (1984) performs a cross-sectional analysis on FTC line-of-business data for 437 firms in 259 four-digit industries. He finds that private R&D is positively associated with government financed R&D using both a restricted intensity version of the relationship, and a log-level version. In both cases, his estimates are robust to the inclusion of firm dummy variables and four-digit industry dummy variables. The results also hold up whether or not firms that have zero company financed R&D are included from the sample. As is the case for many of the studies surveyed here, his analysis may be biased because of endogeneity between public and private R&D, due to omitted variables that drive both sets of funding decisions. At least part of the ''below-firm'' variation across lines-of-business probably is attributable to variation in technological opportunities and appropriability conditions that are affecting the marginal returns. Scott's use of industry dummies should capture some of these omitted variables. But, the recent works of Trajtenberg (1989) and Toole (1999a; b) suggest that variation in technological opportunities is very important even at the product class level.

Leyden and Link (1991) and Leyden et al. (1989) develop a more elaborate structural model in order to provide insight into the empirical relationship between public and private R&D. Since the approach of these two studies is very similar, we will focus on the empirical results of Leyden and Link (1991). The authors estimate a three-equation system using three-stage least squares (3SLS), using a cross-section of firm R&D laboratory data for 1987. Their endogenous variables are laboratory total private R&D budget, laboratory knowledge sharing effort, and government total spending to acquire technical knowledge. For each lab, total government spending is defined broadly to include government contracts, grants, and the value of government financed equipment and facilities.

Leyden and Link's reduced form equations include the following predetermined variables: (1) a dummy variable indicating that the lab has cooperative sharing arrangements; (2) a dummy variable indicating that the lab does basic research; (3) a dummy variable indicating that the lab is oriented toward biological or chemical research; (4) the two-digit industry level R&D/sales ratio; and (5) an interaction term between the R&D/sales ratio and the presence of cooperative sharing arrangements. The excluded exogenous variables in the private R&D equation are essentially the dummy of bio/chem research and the dummy for basic research (the dummy for cooperative sharing arrangements is present in the equation, multiplying the industry R&D to sales, so it is not adding any identification).

The regression model allows government R&D to influence the private R&D budget directly, as well as indirectly through the lab's knowledge-sharing activities. Further, the authors account for potential simultaneity of private and public funding decisions by using the predicted values from a first stage reduced form regression as instrumental variables. They find a positive and significant coefficient on the government R&D in both their private R&D and knowledge sharing equations. Accounting for various feedback effects, this implies an elasticity of

Table 1
Line of business and laboratory studies
See text for details.
OLS = Ordinary least squares; 3SLS = three-stage least squares; FE = Fixed effects.
Where the regression is in levels, the elasticity is derived using the mean levels of R&D spending for the sample.

Author	Time period	Data type	Number of observations	Explained variable (private R&D)	Explanatory variable (public R&D)	Controls	Method	''Net'' findings (elasticity)
Scott (1984)	1974	LB cross-section	3338	log (private R&D)	Log (Government R&D)	Size, firm or industry dummies	OLS (firm, industry effects)	Complementarity (0.06–0.08)
Leyden et al. (1989)	1987	Lab. cross-section	120	US$ Private lab budget	US$ Government R&D funding to lab	Size, lab *K*-sharing, *D* (R&D industry)	3SLS	Insignificant (0.145)
Leyden and Link (1991)	1987	Lab. cross-section	137	US$ Private lab budget	US$ Government R&D and equipment	*R*/*S*, lab *K*-sharing, *D* (chem/bio), *D* (basic R)	3SLS	Complementarity (0.336)
Klette and Moen (1998) (Norway)	1982–1995	Panel within industry (Mach., elec., inst.)	192×3.6	US$ Private R&D Log (private R&D)	US$ Government R&D subsidy log (Government R&D)	Sales, sales sq., cash flow, time dummies	FE OLS	Neither (1 for 1) complementarity (0.06)

0.34 between private and public R&D. Since, in this study, identification of the effect of government R&D on private spending comes primarily from the comparison of labs of different types, it is not surprising that it turns out to be fairly weak.

A different approach is taken in a new study by Klette and Moen (1998), based on panel data on lines of business in Norwegian high-technology firms. Specifically, they looked at the effects of government matching grants in the electronics and electrical equipment sector on the R&D undertaken in the lines of business between 1982 and 1995. This study is one of the few to control for the potential endogeneity of receiving a grant that arises from firm self-selection into the program. [27] Klette and Moen find that government R&D is complementary to private R&D, in the sense that the lines of business do not reduce their R&D effort, but that no additional R&D is induced beyond the level that would have been performed anyway. That is, the 50% that the firm has to put up to receive the grant comes out of their normal R&D budget. Because the authors have a fairly long panel, they are able to look more closely at the dynamic effects of this R&D subsidy program and this yields their most interesting finding: the government subsidy does appear to induce a permanent increase in the level of the line-of-business R&D.

3.2. Firm-level studies

A summary of the firm level studies can be found in Table 2. Hamberg (1966) was the first researcher to use a regression approach on firm level cross-sectional data to address the relationship between public R&D and private R&D. Within the context of a broader exploration of firm R&D activity, Hamberg included a government R&D variable defined to be the total value of Department of Defense contracts divided by gross fixed assets. Separating his sample of 405 firms into industry groups, he regressed the firm's proportion of private R&D employment on its government contracts and other variables for each industry using ordinary least squares. He reported that the government contracts are positively related to private R&D for six out of eight industries (four are significant) and negatively but insignificant for the other two. The four industries showing complementarity are: (1) industrial chemicals; (2) electronic components and communications equipment; (3) other electrical equipment; and (4) office machines. A surprising result was that the coefficient on Defense Department contracts was positive but not significant for the aircraft and missiles industry, because this industry had nearly 90% of its R&D funded by defense contracts during the sample period. Exploration of the timing of the response to these contracts failed to overturn this result. Note, however, that David and Hall (1999) show that a weak response of private R&D spending to public R&D is more likely when the government share of total R&D spending is large (in a specialized technological or labor market area), or when government R&D does not enhance private productivity very much. Both conditions may well apply in the case of this industry (particularly the former).

The analysis of Hamberg (1966) represented a step forward in two important ways. First, he focused on DOD contracts awarded to individual industry groups. The institutional homogeneity of the funding agency and the industry group help limit potential omitted variables bias from other sources of variation like technological opportunities. Second, he included an impressive combination of control variables such as profits, sales, depreciation, gross investment, and a lag of R&D personnel. As we saw in Section 3, these variables help hold constant other factors that may be shifting the firm's marginal returns and cost of funds schedules. However, the cost of the homogeneity of his sample is a small sample size for each regression. His largest industry group had only 34 firms.

Howe and McFetridge (1976) conduct a careful analysis of the impact of Canadian public R&D incentive grants on Canadian private R&D investment. Canadian incentive grants are a cost-sharing arrangement in which public funds are used to support half of the total cost of a private R&D project that the government has decided to support. Motivating their specification using the same investment framework described in Section 3, the authors esti-

[27] See Lichtenberg (1988), Busom (1999) and Wallsten (1999), which are discussed in Sec. 4.2, for other studies that make this correction.

mate a reduced form model of private R&D intensity on government incentive grants and other variables. They use a sample of 81 firms over the period 1967–1971 separated into three industry groups. As in Hamberg (1966), this helps protect against biased estimates stemming from inter-industry differences in product characteristics, technology, appropriability, and other factors. They find a positive coefficient on public incentive grants for all three industries; however, it is significant only for the electrical industry.

Higgins and Link (1981) and Link (1982) analyze how the composition of private R&D investment responds to public R&D support. Using a cross-section of 174 manufacturing firms in 1977, Higgins and Link (1981) find that the percentage of private R&D investment devoted to research falls as the firm receives more public R&D funds. Although they interpret this as evidence for crowding-out, it should be remembered that this is only one portion of a firm's R&D budget. In fact, in an expanded version of this study, Link (1982) finds that federal R&D stimulates total private R&D intensity. When private R&D investment is decomposed into basic, applied, and development components, Link finds that public R&D reduces private basic research intensity. Public funds, however, stimulate private development intensity and have no significant effect on private applied research intensity. While both Higgins and Link (1981) and Link (1982) include control variables accounting for firm profits, diversification, and high-technology orientation, their results are probably affected by unobserved inter-industry variation. Nonetheless, these studies attest to the important point that the type of public R&D support matters for the private R&D investment decision. The distinction made between public R&D contracts and grants in Section 3 is based on the same observation.

Lichtenberg (1984; 1987; 1988) has stressed the econometric issues involved in the analysis of the relationship between public contract R&D and private R&D investment. He has employed a demand and supply framework (similar in spirit to the micro-level investment framework presented here) in order to make two basic points: first, that public R&D contracts should be treated as endogenous at the firm level; second, that sales to government are more R&D intensive and have an effect on private marginal returns that should be included in the specification. In his 1984 paper, Lichtenberg also suggests that the failure of previous studies to account for time constant and unobserved firm characteristics has led to an upward bias on the coefficient estimates. Using data on a cross-section of firms in three different time periods, he presents regression results for private R&D intensity in both level and first-difference specifications (i.e., estimates that control for permanent differences across firms). The mostly positive and significant coefficients on public R&D become negative and significant in the latter regressions, which implies that the observed complementarity was due to firm-level differences in R&D intensities that are correlated with the award of public R&D contracts. Increases or decreases in public R&D funding within the firm were not associated with increases or decreases of private funding. As in all such differenced regressions, however, the potential for downward bias due to measurement error in the independent variable must be kept in mind.

The subsequent papers of Lichtenberg (1987; 1988) address the issues posed by the tendency of federal procurement demand to concentrate on more R&D-intensive products, and the potential endogeneity of federal contracts. His 1987 paper combines firm data from Compustat and the Federal Procurement Data System to construct a panel of 187 firms over the period 1979–1984. He demonstrates that the value of government contracts variable becomes insignificant once government purchases are included separately in the regression equation.

Using a sample of 169 firms from the same database, Lichtenberg (1988) proceeds to further partition federal contracts into ''competitive'' and ''non-competitive.'' While his results show a positive and significant government R&D coefficient for the total and ''within'' OLS regressions, the coefficient becomes negative and significant when he accounts for endogeneity using as an instrumental variable *potential* government contracts for products that the firm produces. It is important to note that the government sales variable in the regression includes the value of government contracts. As he makes clear, his results imply that there is no *additional* effect of government contracts beyond their impact

Table 2
Firm-level studies — (a) US data; (b) Data from other countries
Definitions: E = employment. CS = Cross-section. FE = Fixed effect (within or firm dummies). FD = First differences. IV = Instrumental variables.

Author	Time period	Data type	Number of observations	Explained variable (private R&D)	Explanatory variable (public R&D)	Controls	Method	''Net'' findings (elasticity)
(a)								
Hamberg (1966)	1960	Firm CS within industry	$8\times(\sim 20)$	Private R&D E/ Total E	US$ Government contracts/Assets	Size, depreciation, investment, lag R&D E	Weighted OLS	Mixed/ complementarity
Shrieves (1978)	1965	Firm CS across industry	411	Log (private R&D E)	% Government-finaced R&D	Size, prod mkt, tech opportunity, C4	OLS	Substitutability
Carmichael (1981)	1976–1977	Firm CS within industry (transprotation)	46×2	US$ Private R&D expenditure	US$ Government R&D contracts	Size	Pooled OLS	Substitutability
Higgins and Link (1981)	1977	Firm CS across industry	174	% Research in private R&D	US$ Government-financed R&D	Profit/S, divers., D (hitech)	OLS	Substitutability (-0.13)
Link (1982)	1977	Firm CS across industry	275	Private R&D/sales	Government-financed R&D/sales	Profit/S, divers., C4, D (governance)	OLS	Complementarity
Lichtenberg (1984)	1967, 1972, 1977	Firm CS across industry	991	Change in private R&D/sales	Change in Government R&D/sales	Size	Fixed effects	Substitutability
Lichtenberg (1987)	1979–1984	Panel across industry	187×6	US$ Private R&D expenditure	US$ Government-financed R&D	Year dummies, size, sales to government	Pooled OLS	Insignificant
Lichtenberg (1988)	1979–1984	Panel across industry	167×6	US$ Private R&D expenditure	US$ Government-financed R&D	Year dummies, size, sales to government	FE OLS, IV	Substitutability (IV) complementarity (FE)
Wallsten (1999)	1990–1992	Firm CS across industry	81	US$ Private R&D experienced in 1992	Number of SBIR awards, total value of SBIR awards	Age, size, patents, R&D exp. (1990), D (never apply), industry and geography dummies	OLS, 3SLS	Substitutability

(b)

Howe and McFetridge (1976) (Canada)	1967–1971	Firm panel within industry	6×44	US$ Private R&D Expenditure	US$ Government R&D grants	Size (poly.), profit, deprec, HHI, D (foreign)	Weighted OLS	Mixed/ complementarity
Holemans and Sleuwaegen (1988) (Belgium)	1980–1984	Firm CS across and within industry	5×(~ 47)	Log (private R&D)	log (Government R&D grants)	Size, divers., HHI, D (for.), log (royalties)	FE OLS	Complementarity (0.25–0.48)
Antonelli (1989) (Italy)	1983	Firm CS within industry	86	Private R&D (MM lire), log (private R&D)	% Government-financed R&D, log (government R&D/ total R&D)	Size, profit, D (div), share for. Sales, foreign R/S	OLS	Complementarity (031–0.37)
Busom (1999) (Spain)	1988	Firm CS across industry	147	Private R&D expenditure, R&D per employee	D (participation in subsidy loan program)	Size, patents, export share industry Dummies	OLS with selection correction	Complementarity (0.2) (heterogeneous)
Toivanen and Niininen (1998) (Finland)	1989, 1991, 1993	Panel across industry	133×3	US$ Private R&D expenditure	US$ Government-financed R&D (loans and subsidies)	Investment, cash flow, interest, rate, current and one lag of all variables	FD IV	Substitutability –subsidies to large firms (− 0.10) loans and small firms insignificant

on the firm's marginal returns. As opposed to substitution, it would appear that what Lichtenberg has identified is that the primary impact of government contracts on private R&D investment works though their effect on the firm's private marginal returns, rather than on the firm's marginal cost of funds schedule.

Toivanen and Niininen (1998), Busom (1999) and Wallsten (1999) are the most recent firm-level studies on the public/private R&D relationship. Wallsten focuses on the effects of the US Small Business Innovation Research Program (SBIR). This is a competitive grant program designed to target R&D subsidies to smaller businesses, and Wallsten was able to collect data on firms that have won SBIR awards, firms that applied but were rejected, and firms that were eligible to apply but did not apply. His sample of awardees comes from the data systems of eleven different governmental agencies and covers a variety of industrial areas over the 1990–1992 time period. In order to correct for the potential endogeneity of the public funding decision on the firm's R&D response, Wallsten uses a three-equation system intended to model the award granting process as well as the firm's response. Estimating the system by 3SLS and using the total SBIR budget from which firms could have won awards as his instrument, he finds that the number of SBIR awards won by a firm has a positive but insignificant effect on firm employment. In a separate set of regressions, he finds that the number and value of SBIR awards significantly reduces firm R&D expenditure. In these latter regressions, however, Wallsten is forced to analyze only publicly owned firms and this reduces his sample of firms from 481 observations to 81 observations. Based on the typical size of an SBIR award, Wallsten concludes that public grants displace private R&D investment on a nearly one-for-one basis, although it must be noted that this finding pertains only to the publicly owned recipients of such funding.

Busom (1999) analyzes the effect of Spanish government subsidized loans on private R&D expenditure and employment using a sample of Spanish firms. Like Wallsten (1999), Busom is careful to address the potential endogeneity of the public funding decision stemming from selection bias in the grant process. She explores this problem by implementing a two-step procedure that predicts the probability of participation in the program in the first step, and includes a correction for selection in the second step. Using a sample of 147 Spanish firms in 1988, Busom finds that the hypothesis of no selection bias cannot be rejected, even thought, the legitimacy of pooling participant and non-participant firms is rejected by a Chow test. Unfortunately, her data does not include the amount of the R&D subsidy, only the fact that it exists; so she is unable to provide a quantitative estimate of the complementarity or crowding-out effect. She finds, that on average, receiving a government R&D subsidy induces more private R&D effort than would be predicted on the basis of an R&D effort equation for the ''controls-firms'' (those that did not receive a subsidy), when corrections are made for sample selection biases. For 30% of the firms, however, full crowding-out remained a possibility that could not be ruled out by the data. It will be interesting to see results based on data from this Spanish program in the future, especially those that reveal the amount as well as the presence of the R&D subsidies.

In addition to the typical econometric formulations that regress some measure of private R&D on public R&D, an increasing number of alternative and more indirect approaches have been pursued in recent years. Since these papers are less direct than those considered above, the following brief resumes report only the ''bottomline'' from these efforts. The interested reader is urged to consult the original studies for more detail. First, Irwin and Klenow (1996) analyze a sample of US semiconductor firms to find out how private R&D investment responds when firms participate in a government supported R&D consortium. By finding that membership reduces private R&D investment, the authors suggest that membership eliminates the need for duplicative R&D. Lerner (1999) looks at the long-run impact of the SBIR program on firm sales and employment. He finds that these government grants have only a limited positive impact, except in those areas where there also is substantial venture capital activity. The specification, however, does not allow one to distinguish whether the presence of venture capital funding exerts its effect through shifting the MCC schedule, or whether it is really a surrogate for technological opportunity set differences, i.e., proxying the attraction of biotechnology and software innovations that can be pursued by small firms.

Cockburn and Henderson (1998) analyze the co-authorship of scientific papers between public and private institutions in the US. They find that private firm organization and research productivity are positively related to the fraction of co-authorship with academic institutions, which are largely supported by federal funds. In a closely related study, Narin et al. (1997) examine the contribution of public science to industrial technology using patent citation measures. Their research finds a strong link between industrial patents and publicly supported research. Feldman and Lichtenberg (1998) report finding that for a sample of European Union member countries there is a strong positive relationship between the number of private institutions that specialize in a particular scientific field and the number of public institutions specializing in the same scientific field. They interpret this result as evidence of complementarity between public and private investments in R&D.

3.3. Industry-level studies

There have only been a handful of industry level studies on the relationship between public R&D and private R&D investment, probably because at this level of aggregation the absence of a clear ''experiment'' is most glaring. The most important proximate source of variation in R&D intensity across firms is differences in industry, and this is as true of public R&D as of private R&D expenditures. Therefore we should not be surprised if industry-level studies show complementarity between the two, nor should we conclude anything other than the fact that some industries have greater technological opportunity than others.

The industry studies are summarized in Table 3. The Globerman (1973) and Buxton (1975) papers examine industry cross-sectional variation and find complementarity. However, these studies use very small samples, 15 data points in Globerman (1973) and 11 data points of Buxton (1975). Larger samples and better specifications can be found in Goldberg (1979), Lichtenberg (1984), and Levin and Reiss (1984). Each of these studies use NSF data arranged as a panel with observations on a cross-section of industries over time. Goldberg (1979), following a neoclassical investment approach, regresses private R&D per unit of output on both current and lagged federal R&D per unit of output, plus industry dummies and other control variables. He finds that current federal R&D has a negative and significant coefficient while federal R&D lagged one period has a positive and significant coefficient. The sum of these coefficients indicates a small complementarity effect of federal R&D on private R&D investment.

Lichtenberg (1984), on the other hand, finds that public R&D reduces private R&D investment and employment at the industry level. His preferred specification regresses the change in private R&D investment (or employment) on the change in contemporaneous and lagged federal R&D plus industry dummies, and time dummies. For federal R&D, he concludes that an additional dollar crowds out eight cents of private R&D investment. Introducing better controls for cross-industry variation in technological opportunity and appropriability, however, would tend to remove the upward bias in the estimated coefficient and thus reinforce the indications of crowding-out in this study.

The paper of Levin and Reiss (1984) stands out as the most ambitious industry level study in the literature. They develop a structural equation system that relates an industry's concentration, R&D and advertising intensities to the industry's structure of demand, technological opportunities, and appropriability conditions. In their model, government R&D intensity enters both as a measure of technological opportunity and as a determinant of appropriability conditions. Rather than treat government R&D as exogenous, however, the authors specify a reduced form equation that models government R&D intensity as a function of the government share of industry sales (both defense and non-defense) and of the extent of R&D ''borrowing'' via capital purchases from other industries, along with the opportunity and appropriability variables. Using two stage least squares, Levin and Reiss find that government R&D intensity has a positive and significant effect on private R&D intensity. In all specifications, the authors find a complementary relationship with a magnitude that implies each additional dollar of public funds stimulates from seven to seventy-four cents of private R&D investment.

Table 3
Industry-level studies
All studies use US data unless otherwise noted.
See Table 2 for definitions.

Author	Time period	Data type	Number of observations	Explained variable (private R&D)	Explanatory variable (public R&D)	Controls	Method	''Net'' findings (elasticity)
Globerman (1973) (Canada)	1965–1969	Cross-section	15	R&D *E*/ Total *E*	Government R&D/ sales	*D* (tech opportunity), % foreign, industry conc., sales growth	OLS	Complementarity
Buxton (1975) (United Kingdom)	1965	Cross-section	11	Private R&D/ Gross output	Government R&D/ Gross output	C4, Divers., entry barriers?,	OLS	Complementarity
Goldberg (1979)	1958–1975	Panel	18 × 14	Log (private R&D/ output)	Government R&D/sales (sum of lag 0 and 1)	Industry Dummies, price of *R* lag private *R*/output	FE OLS	Complementarity
Lichtenberg (1984)	1963–1979	Panel	12 × 17	Change in private R&D	Change in Government R&D	Year dummies, industry dummies,	FE OLS	Insignificant
Levin and Reiss (1984)	1963, 1967, 1972	Panel	20 × 3	Private R&D/ production costs	Government R&D/ shipments	Tech dummies, basic *R* share, industry age, HHI	2SLS	Complementarity

A handful of carefully executed case studies may be noticed here, all of which report finding a complementary relationship between public R&D and private R&D investment. The best known study, Mansfield and Switzer (1984), uses interview data collected from R&D executives in private firms. Their study focuses on R&D targeted on energy technologies in the electrical equipment, petroleum, primary metals, and chemical industries. The authors combine the responses from 25 firms to calculate the change in company-financed R&D per dollar of government-financed R&D. They uncover an asymmetric relationship in which the effect of an increase in government R&D has a different magnitude and time profile than a decrease in government R&D. An additional dollar of federal R&D stimulates an additional six cents in the first 2 years and nothing thereafter. A one-dollar decrease, on the other hand, stimulates a twenty-five cent fall in private R&D in the first 2 years and an additional nineteen-cent decrease in the third year. Support for a complementary public–private R&D investment relationship also has emerged from studies of aircraft and civilian space technology, by Hertzfeld (1985) and Mowery (1985).

3.4. Aggregate studies

We have identified seven aggregate macro econometric studies of the public/private R&D relationship in the recent journal literature. These papers are summarized in Table 4. Not only was the Levy and Terleckyj (1983) paper the first of the macro level studies but it remains the most definitive of its kind. Using NSF data for the United States over the period of 1949–1981, the authors explore the impact of government contract and ''other'' R&D on private R&D investment and productivity. Their main findings are: (1) government contract R&D is positively and significantly associated with private R&D investment and productivity; and (2) ''other'' government R&D has no contemporaneous relationship, but does complement private R&D with a lag of 3 years, while reducing private productivity with a lag of 9 years. Even after correcting for government reimbursement of certain private R&D overhead expenditures, Levy and Terleckyj find that an additional dollar of public contract research added to the stock of government R&D has the effect of inducing an additional twenty-seven cents of private R&D investment. Moreover, Terleckyj (1985) shows that this effect remains after accounting for the R&D intensity of governmental demand, to which attention was drawn by Lichtenberg (1984). Yet, Lichtenberg (1987), also using NSF time-series data for the US, reports finding that when allowance is made for the higher R&D intensity of sales to the federal government, there is no additional impact from public R&D expenditures on private R&D investment. That study by Lichtenberg, however, does not replicate the inclusion of controls for other determinants of the aggregate level of private investment and productivity by Levy and Terleckyj (1983), nor does it follow them in defining public and private R&D as stock variables. Although Levy and Terleckyj's approach in the latter regard is a conceptual improvement, because one would expect the effects of R&D investment to persist for longer than 1 year, there is an practical econometric difficulty with its implementation: working with stocks, rather than the annual flows, induces very strong positive serial correlation in the dependent and independent variables of the regression model.

Robson (1993) and Diamond (1998) also conduct aggregate time-series analyses using NSF data for the United States, but they restrict their focus to examining the effects of basic research. This type of federal funding is of the ''infrastructure'' variety which can be expected to shift out the marginal product curve for private R&D; hence, as the analysis in David and Hall (1999) shows, in the long run it is more likely to increase private and total investment in R&D rather than reduce them. Robson (1993) focuses his attention on how private basic research investment responds to various forms of federally funded R&D, separating the aggregate into basic research and government outlays for applied/development R&D performed in industry. Using data for the period of 1956–1988, he regresses the change in private basic research investment on the change in federal basic research expenditures, the level of federal applied/development R&D, the change in private applied/development R&D investment, and the government/non-government ratio of industry sales. Robson finds that both the change in federal basic and the level of federal applied/de-

Table 4
Aggregate studies
All studies use US data unless otherwise noted.
See Table 2 for definitions.

Author	Time period	Data type	Number of observations	Explained variable (private R&D)	Explanatory variable (public R&D)	Controls	Method	''Net'' findings (elasticity)
Levy and Terleckyj (1983)	1949–1981	Time-series	33	US$ Private R&D stock	US$ Government contracts to industry (stock)	Lag output, lag taxes, unemployment age R&D stock, US$ Government R&D, US$ reimbursement	GLS	Complementarity
Terleckyj (1985)	1964–1984	Time-series	21	US$ Private R&D expenditure	US$ Government contracts to industry	Output, government durables, lag R&D in Europe/Japan	GLS	Complementarity
Lichtenberg (1987)	1956–1983	Time-series	28	US$ Private R&D expenditure	US$ Government contracts to industry	Sales, sales to government	OLS	Insignificant (0.045)
Levy (1990) (cross-country)	1963–1984	Panel	9×21	US$ Private R&D expenditure	US$ Government contracts to industry	GDP, country dummies, pred. Europe and Japan private R&D	Pooled GLS	Complementarity
Robson (1993)	1955–1988	Time-series	33	Change in private basic research	Change in federal basic research	Level and chg private appl. *R*, Government appl. *R*, Government purchases, chg in non-government goods in services	OLS — 1st-diff	Complementarity
Diamond (1998)	1953–1993	Time-series	41	US$ Private basic research	US$ Federal basic research	GDP, time trend	OLS — 1st diff Box–Cox	Complementarity (1.04)
Von Tunzelmann and Martin (1998) (cross-country)	1969–1995	Panel	22×27	Change in private R&D	Change in public R&D	Levels of private and public-funded R&D, country dummies	Fixed effects	Complementarity

velopment research have positive and significant coefficients in this regression equation. Diamond (1998) similarly uses NSF data for the earlier portion of the same period (1953–1969) to examine the impact of changes in federal basic research expenditures on changes in basic research spending by industry. He, too, finds a positive and significant coefficient on the federal spending variable.

Thus, both of the foregoing studies conclude that at the aggregate level the overall, the net relationship between public and private investments for basic research is one of complements, not substitutes. Indeed, the estimated the elasticity reported by Diamond (1998) is very high, roughly unitary. It should be noted, however, that as these results are obtained from the co-variation in the aggregate time-series observations, they could be reflecting the correlated effects of other macroeconomic variables. Neither study makes use of instrumental variables to control for the influence of the US business cycle and shifts in overall federal fiscal policy during the period in question.

As an alternative to attempting to control for the possible influences of those omitted variables, a different approach is available where one can make use of cross-country panel data to deal with the endogeneity problem that is likely to plague time-series analyses of a single economy. Indeed, there have been some recent attempts to exploit this possible route to identifying the nature of the public–private R&D relationship, by employing aggregate-level time-series observations for OECD countries in panel form. Starting with a sample of nine OECD countries for the period of 1963–1984, Levy (1990) works with a specification that distinguishes among three geographic regions within which it is assumed that there would be strong spillovers of the effects of public R&D expenditures: the US, Europe, and Japan. He therefore regresses national private R&D investment on aggregate public R&D investment in each region, aggregate regional GDP, and individual country dummy variables. Among the nine countries in his panel, Levy (1990) finds that five countries exhibit significant overall public–private complementarity effects, whereas two countries show significant substitution effects. The reasons for the differences remain unexplored, which is understandable in view of the restricted size of the cross-national sample. Further progress along these lines may be possible in the near future. Research by Von Tunzelmann and Martin (1998) has ambitiously undertaken to develop the R&D time-series for some 22 OECD countries over the 1969–1995 period. Exploratory analysis of this data by von Tunzelmann and Martin is still in progress, but they report preliminary results of using the panel data to fit a linear model relating changes in industry-financed R&D to the changes in the government-financed R&D, and the previous levels of both private and public R&D expenditures, allowing country-specific differences in all the coefficients. In only 7 of the 22 countries do they find that changes in government-funded R&D have any significant impact on changes in industry-funded R&D, with the sign being positive in five of those seven cases. [28] Rather more illuminating results are likely to be obtained by exploiting the availability of this enlarged panel to estimate models whose specifications take account of cross-country differences in the set of structural characteristics that David and Hall (1999) suggests would affect the sign of the aggregate reduced-form relationship between public and private R&D investments.

Because it addresses an essentially macro-level effect, we also should take notice here of the investigation by Goolsbee (1998) of the direct labor market impacts of US government R&D funding. Using NSF data on scientists and engineers (S&E), Goolsbee finds that increases in expenditures for public R&D have a significant effect in raising average S&E wages. He suggests that a major fraction of public R&D yields windfall gains to S&E workers; and that, by raising the cost of technically skilled workers used in private R&D laboratories, government funding tends to ‘‘crowd out’’ private R&D. As we have noted in our earlier discussion (see Sections 2.5 and 2.6) of the R&D input market effects of an exogenous increase — in either public

[28] The countries exhibiting complementarity in this respect are: Germany, the Netherlands, Switzerland, New Zealand and the USA. But the preliminary results overall are decidedly mixed: leaving aside the three countries (among the 22) for which the coefficient on changes in government-financed R&D is both non-significant and close to zero, in 10 of the remaining 18 cases the coefficient is found to be positive.

or private investment levels — the implication of findings such as Goolsbee's is that aggregate-level econometric estimates are likely to overestimate the real response of private R&D investment to public R&D expenditures, because they will include the positive price effects. This may help to explain why the macro-level estimates implied by the findings in Goolsbee's study, and others, tend to be more strongly in favor of complementarity than the general run of the micro-level elasticity estimates surveyed here. [29]

3.5. Micro-level impacts of public R&D performed by non-profit organizations

Adams (1998) and Toole (1999a; b) appear to be the only econometric studies on the relationship between publicly funded/non-profit performed research and private R&D investment in the manufacturing sector. [30] These two studies, however, have very different objectives and use different data and specifications. Adams (1990) is interested in the factors that mediate research spillovers between industrial labs and outside firms and academic institutions. By separating funds devoted to learning activities from the overall R&D budget, Adams is able to investigate the dependence of the level of private R&D upon the stocks of industry R&D and federally funded academic R&D. Using survey data from 208 industrial laboratories in the chemical, machinery, transportation equipment, and electrical equipment industries, he finds that publicly supported academic research does not stimulate industrial learning R&D, although it does stimulate greater expenditures on learning about academic R&D. Even though this line inquiry is on-going, econometric research that separates private R&D investment into different categories, in the same spirit as that of Link (1982), can be expected to improve our understanding of how overall private R&D budgets respond when there are changes in the distribution of public funding for R&D performed by different types of research organizations.

Toole (1999a; b) explores the complementarity between private R&D investment in the US pharmaceutical industry, and publicly funded research performed outside the industry, in public and private non-profit institutes and universities. Since this type of public research affects the private marginal returns to R&D and not the private cost of funds, it is important to hold constant other factors that may shift the private MRR schedule. The analysis attempts to control for these other factors in three ways. First, restricting the analysis to a single industry serves to eliminates a major source of demand shifts arising from the variation in technological opportunities and appropriability conditions. Second, the use of a new and detailed database on public R&D grants and contracts, allows Toole to separate both public and private R&D investment expenditures into seven medical technology classes. This is important since the private marginal returns schedule will differ by the specific technologies and the changes in the state of the art in those technological areas. Third, public and private R&D investment data are matched by technology class over a 15-year period to construct a panel data set. This permits use of an econometric specification that includes both technology class dummies and year dummies. Differences in the marginal returns across classes are picked up by the class dummy variables while R&D price changes and other trends over time are captured by the year dummies.

With additional control variables for regulatory stringency and a correction for the endogeneity of expected profitability, Toole (1999a) finds that public basic research stimulates private R&D investment after a lag. For the estimated lag of 6–8 years, the elasticity of private R&D investment with respect to the stock of public basic research lies in the range of 0.46–0.53. While Toole's analysis does not use an econometric correction for the potential endogeneity of public R&D funding, that is not likely to be a serious problem in this particular context. Unlike the program-oriented analyses by Busom (1999) and Wallsten (1999), there is no program selection bias affecting the for-profit firm's response to this

[29] See David and Hall (1999) for further discussion of the quantitative implications of the estimates of Goolsbee (1998).

[30] The papers by Jaffe (1989) and Ward and Dranove (1995) are part of a broader definition of this literature. Jaffe (1989) looks at geographically mediated spillovers and does not differentiate between publicly and privately funded academic research. Ward and Dranove (1995), on the other hand, separate public and private R&D funding but do not do not differentiate between performers of public R&D.

publicly supported R&D. Moreover, other sources of endogeneity, such as simultaneity bias and omitted technological opportunity variables are minimized, given the estimated lag in the relationship and technology class structure of the model. This much having been said in favor of the use of industry level technology classes, Toole's approach does assume that firm effects are less important than technology class effects. That well may be the case for the more dynamic high-technology industries, but it is less likely to hold for more mature non-science-based industries. It would be revealing, therefore, to carry out a similarly detailed analysis at the firm level, but, unfortunately, the distribution of proprietary R&D investments among specific technological areas is not information that businesses are likely to disclose until it ceases to be regarded as having any future commercial relevance.

4. Summary and conclusions

The discussion introducing this survey elaborated a standard unifying framework within which to examine R&D investment at the microeconomic level. With its help we sought to identify the distinctive channels through which the provision of government subsidies would affect the behavior of business firms, associating those effects with shifts either of the firm's MRR schedule, or of its MCC schedule, or of both.

The implications of the firm-level analysis was compared with the insights obtained from a heuristic structural model of relationships that would obtain at the macro-level, drawing for the latter on the analysis recently presented by David and Hall (1999). Recognition of the existence of heterogeneities and asymmetries among firms, quite apart of problems arising from the interdependence of enterprise behavior in imperfectly competitive markets, was seen to render invalid the attempt to pass from the micro- to the macro-analytic level directly, by separate aggregation of the MRR and MCC schedules and solution of the industry, sectoral or economy-wide equilibrium. This occasions the need for a separate macro-level framework, in which the effects of funding upon the prices of R&D inputs, as well as informational spillovers, can be represented for both the short-run and long-run cases.

In the development of this part of the exposition, simplicity, rather than novelty was the criterion to which the discussion adhered. Its two immediate purposes were to highlight the principal econometric issues that would need to be addressed by the ensuing critical review, and to provide guidance in interpreting the empirical findings reported by the quite diverse array of studies that compose the literature on this topic. Insofar as those goals were met, we believe that a strong initial case has been made for the value of paying greater attention to structural modeling; certainly, for taking structural modeling further than has been the norm for research contributions addressing the issue of whether or not public funding of R&D encourages, or simply substitutes for R&D investments made by business enterprises.

This survey deliberately has eschewed an effort to arrive at any definitive empirical conclusions regarding the sign and magnitude of the relationship between public and private R&D. In doing so, we have acknowledged the multiplicity of the approaches to this question that appear in the literature, and the consequent lack of immediate comparability between studies conducted at differing levels of aggregation, and treating a variety of modes and purposes in government funding of R&D.

Quite apart from the difficulties of rendering the results of those studies in a form that would permit ready quantitative comparisons, the heterogeneity of experience created by the application of institutionally different subsidy programs to diverse industries and areas of technology provides strong grounds for doubting the usefulness of searching for ''the'' right answer. Beyond our commentary on the individual contributions, what, then, it is possible to extract, by way of a valid and intelligible overview of the present state of empirical knowledge on this question?

Guided by insights from the analytical framework, our examination of the literature proceeded by comparing and contrasting empirical studies that first were grouped according to the level of aggregation at which the relationship between publicly and privately funded R&D was examined. In addition an effort was made to distinguish between findings pertaining to the impact of government contracts, and those concerned with other (grant) provisions of funding for R&D. Further, the discussion of the publications arrayed in our comparison, Tables 1–4 noted those contributions that rest exclusively on data about US experience. The latter comprise about two thirds of the 33 sets of results assembled for examination, and keeping in mind this dimension of heterogeneity in the sources of ''the evidence'' — in addition to that arising from variations in ''level of aggregation'' dimension — would seem to be pertinent for a number of reasons. Among the more obvious and straight-forward of these should be mentioned the fact that observations drawn from the third quarter of the century carry considerably greater weight in the body of US evidence than is the case for the studies of experience elsewhere. The comparatively greater importance of defense (and aeronautic and space) contracts for R&D in the total of US government funding for industrially performed R&D, also is a differentiating characteristic that may be significant.

This suggests we should reconsider the shape of the literature explicitly from those two taxonomic perspectives. And, indeed, several striking features of the distribution of overall findings are exposed by the simple tabulation in Table 5, in which our sample of studies are arrayed according to the level of aggregation, and national source of data. As may be seen from the table, exactly one-third of the cases report that public R&D funding behaves as a substitute for private R&D investment. This result is far more prevalent among the studies conducted at the line-of-business and firm level, than among those carried out at the industry and higher aggregation levels — where the relative frequency approaches one-half (9/19).

A second pattern that stands out from the table is that whereas five-sixths of the studies based on data from countries other than the US report overall complementarity, the corresponding proportion among those based purely on US data is only four-sevenths [1–(9/21)]. That has some bearing upon a third feature of interest in Table 5: the regional contrast in the findings that emerges within the group of studies conducted at and below the level of the firm. Here one sees a marked difference between the distribution of the US-based findings and the much higher relative frequency with which complementarity is reported by analysts working exclusively from US evidence.

It may well be that this latter contrast is in part reflecting underlying differences between the character of the US federal R&D contracts and awards, and the purposes and terms of the more recent European government programs of funding for industrial R&D. It should be noted, however, that the frequency with which ''complementarity'' appears among US-based studies pertaining to experience at the line-of-business and firm levels cannot be regarded as being anomalously low; not at least when it is viewed within the overall context of the distribution of findings summarized by Table 5. [31]

Our analysis directed particular attention to the differences one should expect to find in the results of studies that are conducted at different levels of ag-

Table 5
Summary distribution of econometric studies of the relationship between public and private R&D investment

	Studies reporting ''net'' substitution	Total number of studies
Level of aggregation: firm and lower [a]		
Number of studies surveyed	9	19
Based on US data only	7	12
Based on other countries' data	2	7
Level of aggregation: industry and higher [b]		
Number of studies surveyed	2	14
Based on US data only	2	9
Based on other countries' data	0	5
All levels of aggregation [c]	11	33

[a] The findings in Toivanen and Niininen (1998) for large firms and small firms each are counted here as a separate study.

[b] Adams (1998) and Toole (1999a; b) are included here, and are assigned following the text discussion in Section 3.5.

[c] The assignment of Von Tunzelmann and Martin (1998) follows Table 4, although these results are preliminary.

[31] Quite the contrary, this can be seen by taking the analysis of the figure in Table 5 one step further. Consider that the proportion of ''complementarity'' results among all the US-based studies is (4/7), and the fraction of all lower aggregation level studies that report complementarity is (11/19). Under independence of the two effects, therefore, we might expect (4/12) of the US studies based on line-of-business and firm level data to have reported ''complementarity''; whereas the observed frequency is (5/12). This is not a significant deviation from the theoretical expectation, and, in addition, it is in the direction opposite that which superficial examination of the table might suggest.

gregation. It was pointed out that the effects of unobserved inter-industry differences in the technological opportunity set are likely to induce positive covariation in the public and private components of total industry-level R&D expenditures. Further, at the aggregate level, the likely positive effect on R&D input prices of expanded government funding also contributes to the appearance of complementary movements in the private and public components of nominal R&D expenditures. One may note, then, that the summary tabulation of results that we have reviewed (in Table 5) conform well with these theoretical expectations. Complementarity appears more prevalent, and substitution effects all but vanish among the subgroup of studies that have investigated this relationship at the industry and national economy levels.

Is this to be read as telling us something about the strength of the positive impacts that inter-firm and inter-industry spillovers, through knowledge and tangible R&D input markets, have upon the expected private rates of return on company-funded R&D? Or is it reflecting some combination of the endogenous responses of both government and business allocation decisions to opportunities being open by fundamental scientific and technological advances, and the ''R&D price effects'' of the competition generated by private and public funders for limited scientific and engineering resources?

At present, these questions remain open, and no less important than they were when Blank and Stigler (1957) launched the search for answers. Progress towards resolving them will require further, micro-level studies that make a serious effort to control for the effects of cross-section and temporal variations in technological opportunities, along with other sources of variation affecting expected private rates of return. To the extent that government policies affecting public R&D funding are correlated with initiatives intended to enhance appropriability of research benefits by investing firms in areas of new technological opportunity, identification of the former effects from single country analyses will remain difficult. Further utilization of international panel data seems a promising avenue for further work in this as in other connections.

Research using use quasi-experimental (propensity score or sample selection corrections) to comparing ''treated'' firms and ''controls'' offers another line of future advance, especially if it could be coupled with the design of actual policy experiments.[32] This suggests the concluding thought that really important gains in the informational basis for economic policy in this area are only likely to come as a by-product of coupling better policy design with the application of the sophisticated econometric techniques that have now become available.

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[32] See Klette et al. (2000), for further discussion of this point.

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