The Indirect Effects of Public Sector R&D on Economic Performance and Growth

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Abstract

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This study examines the causal relationship between research and development (R&D) and economic growth. In particular, it examines the indirect contribution of public sector R&D to economic performance and growth through its inducement effect on private sector R&D investment. In doing so, this study employs cointegration techniques and uses time-series data from a fifty-year period (1953-2002) in the United States. Empirical results suggest that both public and private R&D contribute to economic performance and growth, but public support to R&D also significantly enhances economic performance indirectly through strong inducements to the private sector's R&D investments.

주제어: 공공부문 R&D, 민간부문 R&D, 경제성장, 유인효과

Keywords: Public Sector R&D; Private Sector R&D; Economic Growth; Inducement Effect

I. Introduction

Knowledge and information are increasingly utilized in production and business activities. The accumulation, availability, and use of knowledge and information are frequently used as indicators of economic growth potential in regional and national economies. Thus, the public sector plays an increasingly important role in the creation, accumulation, utilization, and distribution of knowledge and information. For example, in 1984, 19 state governments in the United States provided tax credits for R&D investment by private companies in their jurisdictions (Chi, 1989). Currently, 31 state governments provide tax incentives on private R&D investment in addition to federal tax credits for private R&D activities (Luger and Bae, 2005; Wilson, 2005). The public sector also spends large amounts of money on R&D activities through academic institutions, national laboratories, and private contracts. Public R&D support constituted approximately 34 percent of total R&D spending in the United States in 2002.

In spite of the increasing emphasis of R&D and technological innovation by academics and policy practitioners in fostering growth in regional and national economies, there lacks general consensus on a causal relationship between technical advances and economic growth. R&D investment and technological innovation can contribute to economic growth, and economic growth can increase the demand for R&D investment. In disaggregating R&D investment by funding source, public support can contribute to economic growth in an indirect way as well as through direct contributions. In other words, if public support to R&D induces R&D investment by private firms, it can foster economic growth *indirectly*.

The objective of this study is to examine the indirect effects of public support to R&D on private R&D behaviour. Whether public support to R&D stimulates and induces private R&D investment is relevant to policymakers, since the public sector spends significant amounts of public money on R&D activities. For empirical analysis the study uses time-series data in the United States and employs cointegration techniques.

The following section (Section II) reviews existing literature on R&D investment and economic growth. In Section III, the variables and data sources used for the causality test are defined, along with descriptive results. Section IV presents Granger causality results. Section V concludes with policy implications. Empirical methodology is covered in details in the Appendix.

II. Review of the Literature

R&D and technological innovation have been important topics in the economic growth literature. Three theoretical explanations are given for a causal link between technological advances and economic growth and for the role of technological advances in promoting economic growth. According to the neoclassical growth model of Solow (1956), technological changes and innovations have profound influences on economic growth and vitality. The rate of technological progress determines the economy's long-run growth rate exclusively, but not vice versa. In this neoclassical model, technological innovations are treated as given and exogenous.

In the late 1980s, however, according to the endogenous growth model proposed by Romer (1986) and Lucas (1988), a bi-directional causal relationship may exist between technological advances and economic growth. In addition to discussing the importance of technological progress for economic growth, as in the neoclassical growth model, these researchers emphasize the feedback effect from the economy to the technological progress. Technology is developed by private firms' investment decisions through increasing returns to scale.

Another endogenous growth model follows Schumpter's idea of "creative destruction" with an emphasis on monopolistic competition (Romer, 1990). This model also implies a bi-directional causality between technological innovation and economic growth. According to Schumpter, as capitalism matures and capital systems progress, the demands for technological innovations grow stronger and more money is invested in research for technological innovation (Rosenberg,2000). The Schumpterian view of endogenous growth emphasizes the public sector's support of R&D (Aghion and Howitt, 1996). In particular, basic research needs to be supported and invested in by the public sector, including governments. Private firms are less willing to invest in basic research than in applied research and development, because they may not be able to capture all the benefits of their basic research. In short, private returns to basic research are lower than social returns because of large spillover effects.

Traditionally, public support to basic research is considered as contributing to the creation of useful codified knowledge and information. According to Martin et. al. (1996), however, this view is "too simple and misleading." Public support to basic research may also increase tacit knowledge and skills, which are essential for individuals and firms to understand and utilize codified knowledge and information. Additionally, Martin et. al.(1996) point out that there are five other forms of economic benefits made through public support to basic research: First, it may contribute to economic benefits through creating new instrumentation and methodologies that can be utilized in either other scientific discipline(s) or industries; second, graduate students are trained to be equipped with tacit knowledge and skills which may help firms find technical solutions and access to recent information and knowledge; third, public funding make sit possible for the community of researchers to be connected through informal contacts, conferences, etc.; fourth, public support to basic research may help solve complex technical problems that domestic firms and researchers may be confronted with; and fifth, it may promote the creation of new high-tech firms.

From theoretical and policy-relevant discussions on R&D and economic growth, it is generally agreed upon that R&D and technological innovation contributes to economic performance and growth. Therefore, it is understood that public support to R&D directly enhances economic performance and growth. But public support to R&D may also enhance economic performance indirectly, i.e., if public R&D support complements and induces R&D expenditures by private firms, then it can positively influence economic growth.

As Martin et. al. (1996) suggest, public support to basic research may induce private firms to utilize publicly available information, knowledge, and expertise for commercial purposes. According to David et. al. (2000), public support to R&D may influence both a private firm's marginal cost of capital (MCC) and marginal rate of return (MRR) in investing its own money on R&D activities. Direct R&D subsidies and cost-sharing arrangements by public agencies may be able to "overcome fixed R&D start-up costs" for private firms, in particular for small firms that have limited financial resources. Public R&D support may enhance the marginal rate of return in three broad ways:

> … (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. In the cases of (a) and (c), the technological knowledge and market information associated with publicly funded R&D performed by one firm could result in "spillovers." ⋯ 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 "infrastructure knowledge" — general principles, research tools and techniques, and skill acquisition that raised the expected rates of return on commercially oriented, applied R&D projects. (David et. al., 2000: 505)

In addition to the possible effects of public support to R&D on a private firm's marginal cost of capital and marginal rate of return, public R&D support may increase a firm's demand for private R&D, because a greater availability of public R&D could decrease the marginal cost of production and increase its level of production, thus resulting in investment of more of its own money on R&D activities.

However, there exist strong counter-arguments against the hypothesis that public support to R&D complements and stimulates private R&D investment (David et. al., 2000; García-Quevedo, 2004). First, public R&D support may displace private financing of R&D efforts. When public money is invested in the targeted technological development areas in which private money will be invested, public support may substitute for private efforts. Second, public R&D support may make the prices of R&D inputs up, because publicly supported R&D programs may increase labor costs through scientific and engineering personnel hires, and increase the costs of capital and materials. To that end, public support to R&D may substitute private efforts of R&D activities and result in a reduced level of private R&D investment.

This study is characterized as a macro-level study, because it focuses on the contributions of public R&D support to economic performance and its inducement effect on private R&D investment, and in doing that it utilizes U.S. national data. Macro-level analysis may be able to provide a better picture of the relationship among public R&D, private R&D, and economic growth than micro-level analysis, because macro-level analysis can capture overall R&D spillover effects more completely than micro-level analysis. Zachariadis (2004) states that the positive effect of R&D on output and productivity growth in the aggregate economy is greater than its effect in the manufacturing sector and industries. David et al. (2000) note that although empirical findings from both micro- and macro-level studies in the existing literature suggest more inducement effects of public R&D support on private R&D investment than its substitution effects, the inducement effects are more dominant in macro-level empirical studies than in micro-level studies.

III. Data and Descriptive Analysis

As mentioned in the previous section, this study examines the causal relationship between total R&D and economic growth. It also examines the causal relationships among public R&D, private R&D, and economic growth. Total R&D ($R\&D^T$)is defined as:

$$R\&D^T = R\&D^G + R\&D^P \tag{1}$$

where $R\&D^G$ and $R\&D^P$ are public R&D and private R&D, respectively. Economic growth is represented by gross domestic product (GDP). All variables are presented in the natural logarithm form (e.g., $\ln GDP$). $\Delta\ln GDP$, $\Delta\ln R\&D^T$, $\Delta\ln R\&D^G$,and $\Delta\ln R\&D^P$ represent the growth rates of GDP, total R&D, public R&D, and private R&D, respectively.

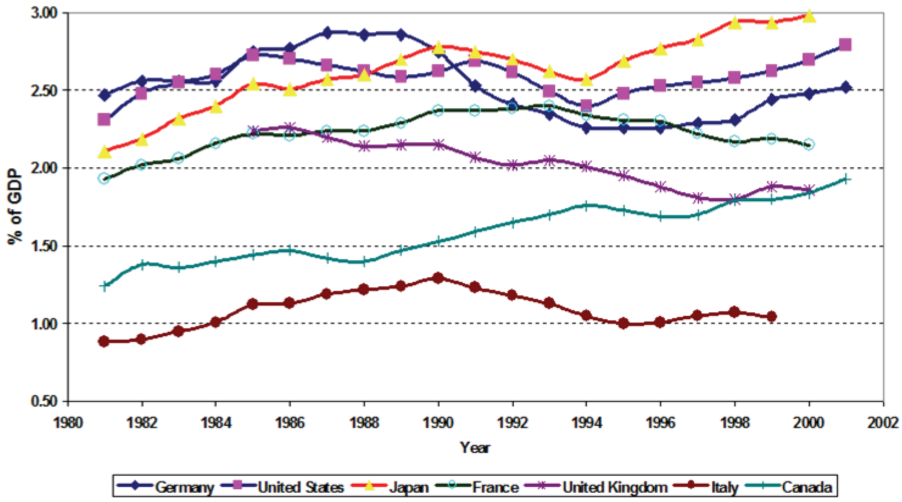
Based on funding sources, total R&D is disaggregated into the R&D activities supported by the following five sectors: federal government, industries, universities and colleges, the non-profit sector, and non-federal governments. $R\&D^G$ is defined as the R&D activities supported by the public sector, including federal government, universities and colleges, the non-profit sector, and non-federal governments. $R\&D^P$ is defined as the R&D activities supported by private industries. Annual data on R&D and GDP from 1953 to 2002 were obtained from the National Science Foundation (NSF) and the Bureau of Economic Analysis (BEA). All variables are expressed in constant 2002 dollars.

As Fig. 1 shows, the United States has a larger R&D intensity to GDP than other

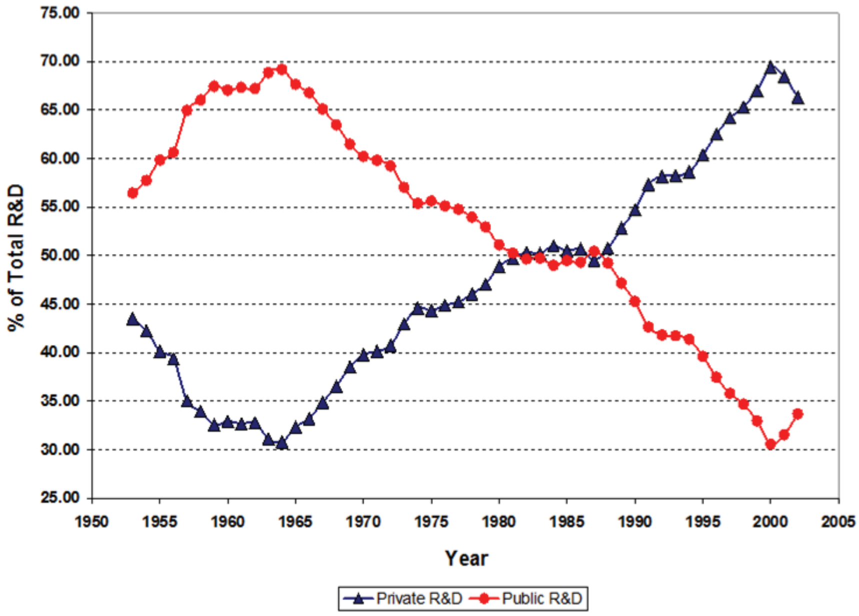
G-7 countries, except Japan. Fig.2 shows that public R&D investment as a share of GDP dramatically increased in the 1950s and 1960s in the United States, but then decreased. By contrast, private R&D investment continuously increased from 1953 to 2002. Accordingly, total R&D investment showed a pattern similar to that of public R&D investment until the late 1970s, but after that, the pattern was more similar to that of private R&D investment. According to Fig. 3, public R&D investment occupied a larger portion of total R&D investment than private R&D investment until 1981. Since then, private R&D investment increased much faster than public R&D investment. For example, public R&D investment was about 1.3 times as large as private R&D investment in 1953, but the former was just one-half of the latter in 2002.

IV. Empirical Results: R&D and Economic Growth

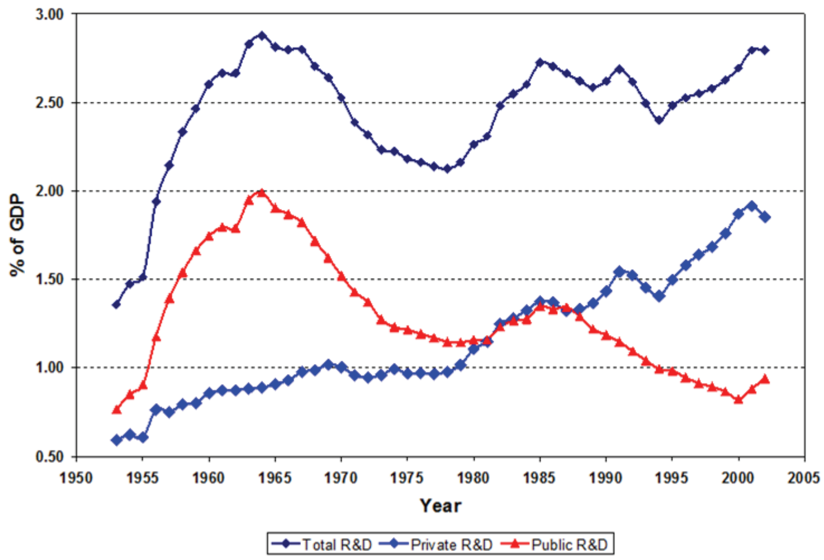
All variables are stationary in their levels, so we can utilize the vector error correction (VEC) model in testing long-run as well as short-run causal relationships between GDP and R&D investment. (For empirical methodology and test results for stationarity and cointegration and for estimation of the VEC model, see the Appendix.)



<Fig 1> R&D as share of GDP in G-7 countries



<Fig 2> R&D as share of GDP in the U.S.



<Fig 3> Public R&D and private R&D as share of total R&D in the U.S.

In this section, a causal relationship between GDP and aggregate R&D investment will be tested followed by a causal relationship among GDP, public R&D investment, and private R&D investment. In particular, a causal relationship between public and private R&D investment will be examined, which will show whether public support to R&D induces or substitutes R&D spending by the private sector in the United States. In this section, three types of Granger causalities will be examined: "short-run" causality, "long-run" causality, and "overall" causality (Ghali and El-Sakka, 2004; Granger, 1988; Zestos and Tao, 2002). The overall Granger causality combines short-run causality and long-run causality. (For more details on Granger causalities, see the Appendix.)

In the VEC model for $\Delta \ln GDP$ and $\Delta \ln R\&D^T$ the optimal number of lagged difference is found to be one, because two lags were previously selected as the optimal lag order (see the Appendix). Thus, the VEC model with one error correction term (ECT) can be written as:

$$\Delta \ln GDP_t = \alpha_1 + \kappa_{GDP}\theta_{1,t-1} + \alpha_{11}\Delta \ln GDP_{t-1} + \alpha_{12}\Delta \ln R\&D^T{}_{t-1} + v_{1t} \quad (2)$$

$$\Delta \ln R\&D^T{}_t = \alpha_2 + \kappa_{R\&D^T}\theta_{2,t-1} + \alpha_{21}\Delta \ln GDP_{t-1} + \alpha_{22}\Delta \ln R\&D^T{}_{t-1} + v_{2t} \quad (3)$$

Table 1 shows the empirical results for the VEC model for $\Delta \ln GDP$ and $\Delta \ln R\&D^T$. The joint F-test results for overall Granger causality are presented under the column $F(2,44)$. In the equation for $\Delta \ln GDP_t$ the ECT is not significant, which implies no long-run causality from total R&D to GDP. The lack of significance for $\Delta \ln R\&D^T{}_{t-1}$ also implies no causal direction from total R&D to GDP in the short run. But the null hypothesis of no overall causality from total R&D to GDP (i.e., $\kappa_{GDP} = \alpha_{12} = 0$) is rejected at the 1 percent level, implying the existence of an overall causality from total R&D to GDP.

<Table 1> Estimated VEC model for $\Delta \ln GDP$ and $\Delta \ln R\&D^T$

	θ_{t-1}	$\Delta \ln GDP_{t-1}$	$\Delta \ln R\&D^T{}_{t-1}$	Constant	F (2, 44)
$\Delta \ln GDP_t$	-0.003	0.044	0.042	0.027	25.092***
	(0.0323)	(0.1600)	(0.0880)	(0.0067)***	
$\Delta \ln R\&D^T{}_t$	0.162	0.255	0.482	0.0004	27.764***
	(0.041)***	(0.204)	(0.112)***	(0.009)	

NOTE: 1. The figures in parentheses are standard errors.
2. *, **, and *** Significant at the 10%, 5%, and 1% levels, respectively.

In the equation for $\Delta \ln R\&D^{T}{}_{t}$, the ECT is significant at the 1 percent level, which implies the existence of a long-run causality from GDP to total R&D. But no short-run causality from GDP to total R&D exists. Since $\Delta \ln R\&D^{T}{}_{t-1}$ is significant at the 1 percent level, total R&D has self-enforcing characteristics. In other words, R&D investment in past years induces further R&D investment in future years. The joint F-statistic value under the column $F(2,44)$ is significantly larger than the critical value at the 1 percent level, which implies the existence of an overall causality from GDP to total R&D.

In summation, test results found the existence of a bi-directional overall causality between total R&D and GDP. These findings suggest that (a) R&D investment promotes economic performance and growth; and (b) at the same time economic growth induces the demand for R&D investment and results in the increased level of R&D investment.

In the VEC model for $\Delta \ln GDP$, $\Delta \ln R\&D^{P}$, and $\Delta \ln R\&D^{G}$, the optimal number of lagged difference is also found to be one, because two optimal lags were previously selected (see the Appendix). Therefore, the VEC model with one ECT can be written as:

$$\Delta \ln GDP_t = \beta_{10} + \lambda_{GDP}\eta_{1,t-1} + \beta_{11}\Delta \ln GDP_{t-1} + \beta_{12}\Delta \ln R\&D^{G}{}_{t-1} + \beta_{13}\Delta \ln R\&D^{P}{}_{t-1} + \varepsilon_{1t} \tag{4}$$

$$\Delta \ln R\&D^{G}{}_{t} = \beta_{20} + \lambda_{R\&D^G}\eta_{2,t-1} + \beta_{21}\Delta \ln GDP_{t-1} + \beta_{22}\Delta \ln R\&D^{G}{}_{t-1} + \beta_{23}\Delta \ln R\&D^{P}{}_{t-1} + \varepsilon_{2t} \tag{5}$$

$$\Delta \ln R\&D^{P}{}_{t} = \beta_{30} + \lambda_{R\&D^P}\eta_{3,t-1} + \beta_{31}\Delta \ln GDP_{t-1} + \beta_{32}\Delta \ln R\&D^{G}{}_{t-1} + \beta_{33}\Delta \ln R\&D^{P}{}_{t-1} + \varepsilon_{3t} \tag{6}$$

Table 2 reports the empirical results for the VEC model for $\Delta \ln GDP$, $\Delta \ln R\&D^{P}$,and $\Delta \ln R\&D^{G}$. Long-run causality is tested against the null hypothesis of $\lambda_{GDP} = 0$, $\lambda_{R\&D^G} = 0$,and $\lambda_{R\&D^P} = 0$, respectively, in Equations 4 - 6. The joint F-test results are shown under the columns $F_1(2,43)$ and $F_2(2,43)$ in each equation. For example, in the equation for $\Delta \ln R\&D^{P}$, the value of $F_1(2,43)$ is the joint F-test statistic value to test against the null hypothesis of no overall causality from GDP to private R&D (i.e., $\lambda_{R\&D^P} = \beta_{31} = 0$), while that of $F_2(2,43)$ is the value used to test against the hypothesis of no causality from public R&D to private R&D (i.e., $\lambda_{R\&D^P} = \beta_{32} = 0$).

The ECT in the equation for $\Delta \ln GDP_t$ is not significant, which implies that no long-run causality exists from public R&D and private R&D to GDP. Neither public R&D nor private R&D Granger causes economic growth in the short run, since neither $\Delta \ln R\&D^G{}_{t-1}$ nor $\Delta \ln R\&D^P{}_{t-1}$ is significant.

<Table 2> Estimated VEC model for $\Delta \ln GDP$, $\Delta \ln R\&D^P$,and $\Delta \ln R\&D^G$

	η_{t-1}	$\Delta \ln GDP_{t-1}$	$\Delta \ln R\&D^G{}_{t-1}$	$\Delta \ln R\&D^P{}_{t-1}$	Constant	$F_1(2,43)$	$F_2(2,43)$
$\Delta \ln GDP_t$	-0.028	0.121	0.035	-0.112	0.026	26.388***	26.402***
	(0.028)	(0.173)	(0.095)	(0.114)	(0.008)***		
$\Delta \ln R\&D^G{}_t$	-0.193	0.277	0.368	-0.098	-0.013	23.289***	22.838***
	(0.036)***	(0.229)	(0.126)***	(0.151)	(0.011)		
$\Delta \ln R\&D^P{}_t$	-0.106	0.847	-0.101	-0.045	0.017	47.630***	41.513***
	(0.037)***	(0.235)***	(0.130)	(0.156)	(0.011)		

NOTE: 1. The figures in parentheses are standard errors.
2. *, **, and *** Significant at the 10%, 5%, and 1% levels, respectively.

In both the equations for $\Delta \ln R\&D^G{}_t$ and $\Delta \ln R\&D^P{}_t$, the ECTs are significant at the 1 percent level. This implies long-run causal directions from GDP and private R&D to public R&D in the equation for $\Delta \ln R\&D^G{}_t$, and from GDP and public R&D to private R&D in the equation for $\Delta \ln R\&D^P{}_t$. But there is no short-run causality from GDP or private R&D to public R&D in the equation for $\Delta \ln R\&D^G{}_t$, since neither $\Delta \ln GDP_{t-1}$ nor $\Delta \ln R\&D^P{}_{t-1}$ is significant. Since $\Delta \ln R\&D^G{}_{t-1}$ is significant at the 1 percent level in the equation for $\Delta \ln R\&D^G{}_t$, public R&D has self-enforcing characteristics. In short, public R&D investment in past years induces further public R&D investment in future years.

By contrast, private R&D does not have self-enforcing characteristics, since

$\Delta \ln R\&D^{P}{}_{t-1}$ is not significant in the equation for $\Delta \ln R\&D^{P}{}_{t}$. Economic grow this a significant driving force in increasing private R&D investment, since $\Delta \ln GDP_{t-1}$ is significant at the 1 percent level in the same equation. But the null hypothesis of no short-run causality from public R&D to private R&D (i.e., $\beta_{32} = 0$) cannot be rejected.

All joint F-statistic values in Table 2 are significantly larger than the critical value at the 1 percent level, strongly suggesting that a bi-directional overall Granger causality exists among all three endogenous variables (i.e., $\Delta \ln GDP$, $\Delta \ln R\&D^{P}$,and $\Delta \ln R\&D^{G}$).

To summarize, test results imply that both public R&D and private R&D contributes to economic performance and growth and at the same time economic growth leads to the increased levels of R&D investment by both the public and private sector. Another interesting result would be the existence of a bi-directional causality between public R&D and private R&D, implying that public R&D investment induces private R&D investment. Thus, public R&D investment also contributes to economic growth indirectly through its inducement effection private R&D.

V. Concluding Remarks with Policy Implications

This study examined the causal relationship between economic growth and the aggregate R&D as well as the disaggregate categories of R&D (i.e., public R&D and private R&D). It employed cointegration techniques to capture the dynamic interactions among endogenous variables under a long-run relationship. It used annual data on R&D and GDP from 1953 to 2002 in the United States.

The empirical results of this study suggest that public support to R&D is necessary and important, not only because of its direct contributions to economic growth but also because of its indirect contributions through inducement effects on private R&D investment. These findings provide valuable policy information on R&D.

That is, public support to R&D induces private spending on R&D in three possible ways: First, it reduces the marginal cost of capital in individual small- and medium-size firms' doing their own R&D activities. Since R&D start-up costs are usually high for individual firms, public support to R&D through direct subsidies and cost-sharing arrangements can significantly reduce the marginal cost of capital, which allows private firms to invest their own money in R&D activities; second, public support to R&D enhances private firms' marginal rate of return from their own R&D efforts, through large spillover effects of public R&D; and third, public R&D support decreases private firms' production costs and increases production levels, which results in the increased demand for their own R&D efforts.

Thus, public support to R&D is essential for individual firms to keep up with new technological innovations and utilize those innovations for their commercial purposes through their own R&D efforts. In addition to public support to R&D, as Teubal et. al.(1996) suggest, active public roles in the distribution of codified and tacit knowledge and information are necessary for small and medium size firms to easily access to and make use of them without additional high costs.

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Appendix: Empirical Methodology

Unit Root Test

Since this study uses time-series data, the stationary properties of all variables must first be examined. Each of the variables must be integrated in the same order before cointegration and Granger causality among the variables are examined. If they are not stationary, the estimated parameters in a regression model are "spurious" (Granger and Newbold, 1974). The estimated model has characteristics such as a high R^2 and alow Durbin-Watson statistic, which makes the usual t-and F-tests on the parameters misleading (Verbeek, 2000, p.281). The regression equation for the Augmented Dicker-Fuller (ADF) test of a unit root is written as:

$$\Delta X_t = \alpha_0 + \alpha_1 X_{t-1} + \sum_{k=1}^{K} \Pi_k \Delta X_{t-k} + u_t \tag{A.1}$$

where X is a vector of the variables used in this study, and u_t is a vector of the error terms with zero mean and constant variance. The null hypothesis for the ADF test is $\alpha_1 = 0$. The t-statistics of the ADF test are compared against MacKinnon critical values. The stationarity of each variable is examined in the variable's level and first-difference.

Since the results of the ADF test are sensitive to lag order, the optimal lag order is determined using the Schwartz Bayesian Information Criterion (SBIC). The value of the SBIC is calculated as:

$$SBIC = \log \frac{1}{T} \sum_{t=1}^{T} u_t^{\,2} + \frac{K}{T} \log T \tag{A.2}$$

where K is the number of parameters and T is the total number of observations. The lag order that has the smallest values for the SBIC is selected.

Table A.1 presents the empirical results of the unit root tests for all the variables used in this study. The optimal number of lags for each variable was selected using the SBIC, which is shown in Table A.1 in brackets.

<Table A. 1> Unit root tests

Level	t-statistic	First-Difference	t-statistic
$\ln GDP$	-2.150 [1]	$\Delta \ln GDP$	-6403*** [0]
$\ln R\&D^T$	-2.620* [2]	$\Delta \ln R\&D^T$	-3.183** [1]
$\ln R\&D^P$	-1.968 [2]	$\Delta \ln R\&D^P$	-5.146*** [2]
$\ln R\&D^G$	-4.240*** [2]	$\Delta \ln R\&D^G$	-2.502** [1]

NOTE: 1. The optimal number of lags are shown in brackets.
2. *, **, and *** Significant at the 10%, 5%, and 1% levels, respectively.

All variables are integrated in the lag order of one (i.e., I(1)) and stationary in their first-differences, since their ADF statistic values are rejected against MacKinnon's critical values at least at the 5 percent significance level. These results allow us to perform cointegration tests to examine whether all variables are stationary together in their levels. The presence of cointegration makes it possible to test long-run as well as short-run causal relationships among endogenous variables.

Cointegration Test

Even though all variables are stationary in their first-differences but not in their levels, they can be cointegrated if they have a linear combination that is stationary. Suppose three variables, $\ln GDP_t$, $\ln R\&D_t^G$, and $\ln R\&D_t^P$ are individually integrated in the order of one (i.e., I(1)), not in the order of zero (i.e., I(0)). The combination of these variables, Z_t ,can still be integrated in the order of zero, as below:

$$Z_t = \gamma_1 \ln GDP_t + \gamma_2 \ln R\&D_t^G + \gamma_3 \ln R\&D_t^P \sim I(0) \quad \text{(A.3)}$$

in which case the three variables are said to be cointegrated (Ansari et al., 1997). The existence of cointegration guarantees a long-run equilibrium relationship between the variables; these variables fluctuate around the long-run equilibrium. The presence of a cointegrating relationship can be investigated using the Johansen cointegration test (Johansen, 1988, 1991; Johansen and Juselius, 1990). There are two statistics for testing a cointegration relationship: the likelihood ratio test (or trace test) statistic and the maximum eigenvalue test statistic. The presence of cointegration makes it possible to use the vector error correction (VEC) model, which explains the short-run behavior of these variables under a long-run cointegrating relationship.

The Johansen cointegration test was conducted to determine whether a cointegration relationship exists between $\ln GDP$ and $\ln R\&D^T$ or among $\ln GDP$, $\ln R\&D^P$, and $\ln R\&D^G$. After each vector autoregression (VAR) model was run with undifferenced data using the SBIC, two lags were selected as the optimal lag order. Tables A.2 and A.3 present the empirical results for the likelihood ratio tests (or trace tests) and the maximum eigen value tests. The results strongly suggest that only one cointegration equation exists.

<Table A. 2> Cointergration results for Unit root tests $\ln GDP$ and $\ln R\&D^T$

H_0	H_1	λ_{max}	1% Critical Values	λ_{trace}	1% Critical Values
$r=0$	$r\geq 1$	18.8241***	18.63	24.1671***	20.04
$r\leq 1$	$r\geq 2$	5.3430	6.65	5.3430	6.65

NOTE: *** Significant at the 1% level.

The cointegration equation for $\ln GDP$ and $\ln R\&D^T$ is presented with only intercept in Equation A.4, and θ_{t-1} is the one-year lagged error term:

$$\theta_{t-1} = \ln GDP_{t-1} - 0.9883 \ln R\&D^T{}_{t-1} - 3.7668 \tag{A.4}$$

Equation A.4 clearly shows that GDP is positively related to total R&D investment in the long run. The coefficient for total R&D is very close to 1 in magnitude.

<Table A. 3> Cointegration results for $\ln GDP$, $\ln R\&D^G$,and $\ln R\&D^P$

H_0	H_1	λ_{max}	1% Critical Values	λ_{trace}	1% Critical Values
$r=0$	$r\geq 1$	29.4107***	28.83	48.6933***	40.49
$r\leq 1$	$r\geq 2$	12.7679	21.47	19.2826	23.46

NOTE: *** Significant at the 1% level.

When total R&D is disaggregated into private R&D and public R&D, each one may have different long-run relationships with GDP growth. The cointegration equation for $\ln GDP$, $\ln R\&D^P$,and $\ln R\&D^G$ is presented with one-year lagged error term, η_{t-1} in Equation A.5, and it has only intercept:

$$\eta_{t-1} = \ln GDP_{t-1} - 0.7655 \ln R\&D^P{}_{t-1} + 0.8842 \ln R\&D^G{}_{t-1} - 17.1277 \tag{A.5}$$

As Equation A.5 shows, private R&D and GDP growth have a positive long-run relationship, while public R&D and GDP growth have a negative long-run relationship. There are two possible reasons. First, a large portion of public sector R&D (in particular, federal R&D) had been taken for the purpose of military defense (see Rosenberg, 1985). R&D expenditures for military defense are not directly related to economic growth and performance. Second, national and foreign events such as the Vietnam War dramatically increased R&D investment for military defense, regardless of the national economy. Most spending for defense R&D goes to aircraft and missiles and electrical machinery (see Rosenberg, 1985).

Vector Error Correction (VEC) Model and Granger Causality

If all endogenous variables are cointegrated, the VEC model for $\Delta\ln GDP_t$, $\Delta\ln R\&D^G{}_t$,and $\Delta\ln R\&D^P{}_t$ can be constructed. Each endogenous variable is a function of its own lagged differences, the lagged differences of the other two endogenous variables, and the one-year lagged error correction term (ECT). The VEC model can be written as:

$$\Delta\ln GDP_t = \beta_{10} + \lambda_{GDP}\eta_{1,t-1} + \sum_{j=1}^{J}\beta_{11,j}\Delta\ln GDP_{t-j} + \sum_{j=1}^{J}\beta_{12,j}\Delta\ln R\&D^G{}_{t-j} + \sum_{j=1}^{J}\beta_{13,j}\Delta\ln R\&D^P{}_{t-j} + \varepsilon_{1t} \tag{A.6}$$

$$\Delta\ln R\&D^G{}_t = \beta_{20} + \lambda_{R\&D^G}\eta_{2,t-1} + \sum_{j=1}^{J}\beta_{21,j}\Delta\ln GDP_{t-j} + \sum_{j=1}^{J}\beta_{22,j}\Delta\ln R\&D^G{}_{t-j} + \sum_{j=1}^{J}\beta_{23,j}\Delta\ln R\&D^P{}_{t-j} + \varepsilon_{2t} \tag{A.7}$$

$$\Delta\ln R\&D^P{}_t = \beta_{30} + \lambda_{R\&D^P}\eta_{3,t-1} + \sum_{j=1}^{J}\beta_{31,j}\Delta\ln GDP_{t-j} + \sum_{j=1}^{J}\beta_{32,j}\Delta\ln R\&D^G{}_{t-j} + \sum_{j=1}^{J}\beta_{33,j}\Delta\ln R\&D^P{}_{t-j} + \varepsilon_{3t} \tag{A.8}$$

where $\eta_{1,t-1}$, $\eta_{2,t-1}$,and $\eta_{3,t-1}$ are the ECTs in Equations A.6 - A.8, respectively. The coefficient of each ECT represents the direction and speed of adjustment of the left-hand-side variable in each equation, in response to temporary deviations from a long-run equilibrium. For example, if λ_{GDP} in Equation A.6 is significantly negative, it would imply a positive response of GDP growth to fluctuations that deviate from the long-run equilibrium.

The estimation of the VEC model allows us to test three types of Granger causality: "short-run" causality, "long-run" causality, and "overall" causality Ghali and El-Sakka, 2004; (Granger, 1988; Zestos and Tao, 2002). If the ECT is significant in an equation, this implies that a long-run causality from the right-hand-side variables to the left-hand-side variable exists in that equation. But when there are more than two endogenous variables in the VEC model, as in this study, it is difficult to know from which right-hand-side variable(s) a long-run causality goes to the left-hand-side variable. Long-run causality is tested against the null hypothesis of $\lambda_{GDP} = 0$, $\lambda_{R\&D^G} = 0$,and $\lambda_{R\&D^P} = 0$, respectively, in Equations A.6 – A.8. According to Zetos and Tao (2002), at least one of these null hypotheses must be rejected to support a long-run causality.

When all the lagged differences of a right-hand-side variable are jointly significant, this implies the existence of a short-run causality from the right-hand-side variable to the left-hand-side variable. For example, when the null hypothesis of $\beta_{12,1} = \beta_{12,2} = ... = \beta_{12,J} = 0$ is rejected in Equation A.6, we can say that public R&D Granger causes economic growth in the short run. The overall Granger causality, which combines short-run causality and long-run causality, can be also examined. For example, the null hypothesis of $\lambda_{GDP} = \beta_{12,1} = \beta_{12,2} = ... = \beta_{12,J} = 0$ in Equation A.6 can be tested using a joint F-test technique to examine an overall causality from public R&D to economic growth.