The Impact of R&D on the Singaporean Economy

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Abstract

There has been a pronounced increase in research and development (R&D) expenditure in Singapore over the last two decades, with government spending accounting for a sizeable share. This increase has been spurred by public policy emphasis on research and innovation as engines of economic growth. This paper analyses the impact of R&D on economic performance in Singapore from 1978 to 2012 through the use of time series analysis. The Cobb-Douglas based analysis shows a long-run equilibrium relationship between Total Factor Productivity (TFP) and R&D investments. We found that the short-run productivity of R&D in Singapore is comparable to smaller advanced economies in the Organisation for Economic Co-operation and Development (OECD). However, in terms of long-run R&D productivity, Singapore lags slightly behind the smaller OECD nations and far behind the G7 countries. This suggests leakage of value capture and low absorptive capacity in local firms. Possibility of productivity improvements induced by policy changes in the 1990s was considered, but no evidence of significant structural breaks was found. Lastly, Granger causality analysis reveals that public sector R&D augments private sector R&D capital, thus playing an important role in generating externalities and spillover effects. Policy implications and lessons for other middle-income countries are discussed.

Keywords
R&D investment, total factor productivity, newly industrialized economies, Singapore
JEL Classification: O57, O47, O30

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1. INTRODUCTION

Total R&D expenditure in Singapore has been increasing steadily since the 1970s, with a more pronounced increase in spending on R&D observed over the last two decades. This increase in R&D spending has been spurred by public policy emphasis on research and innovation as engines of economic growth. Since the first national science and technology plan was announced in 1991 and with each subsequent plan, the government has committed increasingly large budgets to publicly funded R&D and for building infrastructure to support research-intensive activities in both public and private sectors. This has led to questions about the impact of these R&D investments. There is evidence that R&D investments have strengthened certain sectoral clusters, such as the life sciences cluster (Wong, Ho, & Singh, 2010). However, the socio-economic return on R&D investment at the macroeconomic level has not been evaluated recently. Of specific interest is the question of whether R&D has contributed to economic growth in Singapore overall.

The mechanisms through which R&D improves economic performance have been extensively studied and are well established. There is a substantial body of empirical literature showing that R&D is a major contributor to economic growth through the expansion of resource bases & by increasing the efficiency of resource utilization (Fagerberg, 1994; Grossman and Helpman, 1991; Jones, 1995; Stokey, 1995). However, very little of this empirical literature is focused on individual Newly Industrialized Economies (NIEs) and developing economies, although a number of cross-country studies do cover both advanced and middle income economies (see e.g., Lichtenberg, 1992; Wong, Ho, & Autio, 2005). In the context of Singapore, Ho, Wong, and To (2009) examined the impact of R&D on productivity over the period 1978 to 2001, finding evidence of a stable long-run relationship and relatively low R&D elasticity value compared to the OECD average. Given that the level of R&D in Singapore has increased substantially since the early 2000s, this paper provides updated empirical estimates for the impact of R&D on the economic growth of Singapore up to 2012, and examines if there has been structural changes to this relationship in the last decade. In addition, this paper explores the possible causality link between public and private R&D to test the proposition that public R&D spending has spillover effects that benefit the private sector.

2. R&D INVESTMENT AND POLICY IN SINGAPORE

Table 1 shows the trend in total R&D expenditure in Singapore from 1978 to 2012, in real terms and as a percentage of GDP. The changing trends of Singapore's R&D expenditure reflect the distinct development phases of the national innovation system (NIS) and the corresponding shifts in policy focus (Wong, Ho, & Singh, 2007; Wong & Singh, 2008). In the 1960s and 1970s, R&D spending levels were low, with policy emphasis placed on developing operating capability as the nation embarked on export-led industrialization driven by direct foreign investment. In the 1970s through to the 1980s, R&D spending rose as Singapore began transitioning into a NIE and the development strategy shifted towards building process adaptive capability. Since the early 1990s, there has been an emerging shift towards developing innovative capability. This shift towards innovation accelerated in the late 1990s in tandem with the new national prerogative of developing a knowledge-based economy (KBE). R&D investment now takes centre stage as a key pillar of Singapore's development strategy and long-term aim to become among the most research-intensive and entrepreneurial nations in the world. Unsurprisingly, the post-1990 period witnessed marked increase in the levels of R&D expenditure; initially to develop indigenous capacity to conduct applied R&D, and in more recent years to foster the creation and commercialization of intellectual capital to support knowledge-based economic growth. In 2001, R&D spending grew to over 2% of the gross domestic product (GDP) for the first time. At its peak in 2008, total spending on R&D accounted for approximately 2.6% of Singapore's GDP. In the aftermath of the 2008 global financial crisis, R&D expenditure as a percentage of Singapore's GDP fell to 2%, the lowest of the decade, and has been at approximately 2.1% since then.

Beginning in the 1990s, a series of policies was introduced to intensify the use of technology to drive innovation in Singapore. In 1991, the Singapore government launched the first National Science and Technology (NSTP) 5-year Plan to boost investment and research and development activities. This initiative also brought about the establishment of the National Science and Technology Board (NSTB) as the government arm overseeing R&D and technology development. The second 5-year NSTP was established in 1995 and provided S$4 billion to be invested in R&D; in 2000 the third 5-year NSTP added an additional S$6 billion to strengthen Singapore's R&D capabilities.

Given the vulnerabilities of Singapore as a small open economy heavily reliant on international markets, it has been imperative to identify strategic technology areas for competitive advantage. Public sector R&D resources are channeled to develop capabilities in these areas, especially in emerging technologies which have not established enough commercial viability to attract private sector R&D investment. With increased emphasis placed on public sector R&D and focus areas identified, organizational changes were made to the government's structures for R&D promotion. In the year 2000, NSTB was restructured and consolidated to become the current Agency for Science and Technology (A*STAR). Under the A*STAR umbrella, the Biomedical Research Council (BMRC) and the Science and Engineering Research Council (SERC) were established to oversee the key elements of Singapore's S&T policy. The BMRC funds and supports research in the Biomedical Sciences Initiative, which was launched to develop the biomedical sector as one of the pillars of Singapore's economy. It oversees nine public research institutes and centers (PRICs) that conduct mission-oriented research in life sciences, as well as two research consortia that coordinate capabilities across different organizations in the biomedical sector value chain. The SERC, on the other hand, promotes and supports public R&D in the physical sciences and engineering. It oversees eight PRICs that conduct research in fields relevant to the other three pillars of the economy – the Electronics, Engineering and Chemicals sectors.

In 2005, it was announced that a further S$13.5 billion in public funding would be allocated in the fourth NSTP for the period 2006 to 2010. In 2006, the National Research Foundation (NRF) was established as part of the Prime Minister's Office, marking a structural reorganization of R&D policy decision-making. The NRF sets the national direction for R&D by developing policies, plans, and strategies for research, innovation and enterprise. It also funds strategic initiatives and builds R&D capabilities by nurturing research talent. NRF features prominently in the fifth 5-year plan, which was announced in 2010 and covers the period from 2011 to 2015. Formerly the NSTP, the plan was renamed the Research Innovation Enterprise Plan (RIE2015), reflecting the evolution in policy framing of R&D by placing the role of R&D in the economy in context – to create value by stimulating innovation and economic opportunities.

The emphasis on public sector investment in R&D can be seen in the last column of Table 1. Since the early 1990s, public sector spending (including universities and other institutes of higher learning) on R&D has consistently accounted for more than a third of total R&D investment. From 2001 onwards, public sector R&D has been maintained at close to 1% of the GDP. In early 2016, at the unveiling of the RIE2020 plan, the government reiterated its commitment to sustain public R&D spending at these levels.

TABLE 1. R&D Expenditure in Singapore, 1978-2012

Year	Total R&D Expenditure (2000 prices), SGD Million	R&D Expenditure as Share of GDP (%)	Public & IHL Sector Share of R&D Expenditure (%)
1978	66.11	0.21	32.5
1979	80.16	0.23	36.6
1980	92.95	0.24	40.9
1981	114.02	0.27	45.4
1982	150.84	0.33	47.0
1983	202.06	0.41	48.6
1984	277.79	0.51	50.2
1985	337.79	0.63	46.7
1986	411.93	0.76	43.2
1987	496.13	0.82	39.8
1988	540.27	0.81	41.8
1989	597.22	0.81	43.8
1990	657.91	0.81	45.9
1991	833.94	0.96	41.6
1992	1036.00	1.12	39.2
1993	1053.17	1.02	38.0
1994	1195.50	1.04	37.3
1995	1345.81	1.10	35.5
1996	1738.73	1.32	36.8
1997	2021.07	1.42	37.5
1998	2427.06	1.74	38.4
1999	2691.94	1.82	37.1
2000	2939.90	1.82	38.0
2001	3228.83	2.02	36.7
2002	3443.20	2.07	38.6
2003	3522.20	2.03	39.2
2004	4005.72	2.10	36.2
2005	4420.87	2.16	33.8
2006	4753.32	2.13	34.3
2007	5681.08	2.34	33.2
2008	6485.71	2.62	28.2
2009	5310.68	2.16	38.4
2010	5704.22	2.01	39.2
2011	6496.60	2.16	37.9
2012	6227.03	2.02	39.1

3. RESEARCH QUESTIONS AND METHODOLOGY

3.1. Research Questions

This paper attempts to answer three research questions about the impact of R&D on Singapore's economy. First, we examine the relationship between R&D capital and total factor productivity (TFP). In this regard, TFP is a measure of economic growth because it quantifies the portion of GDP growth which is not attributed to increase in physical capital and labour inputs. We seek in particular to establish whether there is a stable non-spurious long-run relationship between R&D and TFP. The existence of such an equilibrium relationship would empirically confirm the contribution of R&D to the economy. This analysis also yields an indicator of R&D productivity, as measured by the elasticity of R&D with respect to TFP; we then compare the R&D productivity estimates for Singapore with those from other economies.

Secondly, we turn our attention to the raft of policy initiatives introduced since the 1990s to boost R&D capabilities in Singapore. We focus on three policy shifts: the first marked by the 5-year NSTP in 1991 which created the NSTB as a focal agency for public sector research; the second reflected in the 1995 NSTP which injected a large amount of public funding for R&D activities and identified key areas for capability development; and lastly, the major restructuring of the NSTB and introduction of new cluster development mechanisms such as the Biomedical Science Initiative in 2000. Our analysis will examine whether these policy changes had any significant influence on R&D productivity.

Thirdly, we attempt to establish whether the sizeable investment in public science has stimulated R&D activities in the private sector. The "social returns" generated by public R&D investments is a topic that has been studied extensively in the economics literature. In addition to the direct effects on productivity, R&D investments are known to result in externalities and spillovers. R&D outcomes achieved by the private sector depend not only on private sector efforts, but also on the pool of knowledge that is accessible to the private sector; the outcomes of public R&D contribute significantly to this knowledge pool. R&D performed by government agencies, for example, has historically been a major source of technologies for the private sector (Wade, 1990). We hypothesize that increases in public sector R&D expenditure stimulate the private sector to conduct more R&D and invest more heavily in R&D activities. The reverse is not expected, however; innovation in the private sector is typically protected for reasons of corporate competition, and flows into the public domain knowledge pool are therefore more restricted.

3.2. Methodology

This paper uses time series data, applying the Cobb-Douglas based analysis summarized by Nadiri (1993). While many studies have adopted this approach using firm and industry level data, studies at the aggregate national level are relatively uncommon. As shown by Griliches (1992), estimates of R&D effects on productivity are dependent on the level of aggregation of the data used. Due to the existence of R&D spillover effects, macroeconomic effects cannot be directly inferred from firm or industry level estimates. To accurately gauge the macroeconomic effects of R&D investment, macroeconomic level data must be used directly.

In this paper, as in Ho, Wong, and Toh (2009), we adopt the two-step productivity approach (Terleckyj, 1974), in which total factor productivity (TFP) is first derived from the underlying Cobb-Douglas production function. Readers may refer to Terleckyj (1974), the Australian Industry Commission (1995) and Guellec and Pottelsberghe de la Potterie (2001) for the derivation of the TFP equation from the log form of the Cobb-Douglas function.

$$\text{Log } Y - \alpha \log K - \beta \log L = \log B + \gamma \log S + \phi \log Z \qquad (1)$$

where:
Log B = constant
S = Stock of knowledge capital (R&D capital stock)
Z = other factors that affect productivity (e.g., education)

The expression on the left hand side of Equation (1) describes exactly the definition of TFP as the increase in output (log Y) that is not explained by changes in capital (log K) and labor (log L), otherwise referred to as the "Solow residual." In the second step, observations of TFP over time are regressed on knowledge stocks and other possible observable determinants of total factor productivity.

$$\text{TFP} = \log B + \gamma \log S + \phi \log Z \qquad (2)$$

R&D expenditures are usually expected to yield results after some period of time rather than immediately. Thus, equation (2) is treated more appropriately as a long run relationship. The residuals from estimating equation (2) may be tested to establish the existence of a co-integrated long run equilibrium relationship between TFP and its determinants, log S and log Z. The advantage of the formulation in equation (2) is in its parsimony and the ready availability of data required for its estimation. On the other hand, a potential drawback of this formulation is the implied assumption of the separability of R&D investments and conventional inputs of labor and physical capital, a limitation pointed out by Griliches (1979) and Sterlacchini (1989). This fails to fully reflect the real world situation, where R&D and innovative activities are more likely to be complements to capital and labor rather than substitutes (Nelson, 1981). R&D may improve productivity or other inputs and may also alter the rates at which other inputs can be substituted into the production process. Conceptually, it is possible to overcome this through the inclusion of interactive terms in more complex models. However, this entails a substantial loss of degrees of freedom which would not be feasible for our analysis, given the relatively short time-series of Singapore data available.

If a co-integrated relationship is found, there will be an error correction model (ECM) representation of the variables, as stated by the Granger Representation Theorem. The ECM describes the short-run relationship between the co-integrated variables, and can also be expressed as an autoregressive distributed lag (ADL) model (Davidson & MacKinnon, 1993). If TFP, log *S*, and log *Z* are co-integrated, assuming a ADL(*x,y*) form, the short-run relationship is

$$TFP_t = \beta + \lambda_1 TFP_{t-1} + \ldots + \lambda_x TFP_{t-x} + \gamma \log S_t + \ldots + \gamma_y \log S_{t-y} + \phi \log Z + \ldots + \phi_y \log Z_{t-y} \quad (3)$$

Where:

γ (coefficient on $\log S_t$) = Short- term elasticity of TFP with respect to knowledge stock.

The Cobb-Douglas approach requires the annual stream of R&D investments to be converted to R&D capital stock. Following studies such as Mohnen, Nadiri, and Prucha (1986) and Coe and Helpman (1995), R&D capital stock is derived by applying the perpetual inventory method using the following formula:

$$S_t = (1-\delta)\, S_{t-1} + R_{t-1} \quad (4)$$

Where

S_t = Stock of R&D capital at time t (in constant prices)

R_t = Expenditure on R&D during period (in constant prices)

δ = Depreciation rate of knowledge

We are able in this paper to extend the analysis in Ho, et al. (2009) and derive more insights on the policy implications of R&D expenditure in Singapore due to the longer time series of data available. This paper also applies two additional methods of time series analysis – the Chow Test for structural break in the relationship between TFP and R&D capital stock, and the Granger Causality test for directional causality between public and private sector R&D.

3.3. Data Sources

Annual data on Singapore for the years 1978 to 2012 were used in the derivation of TFP values, the construction of R&D capital stock, and the estimation of both the long-run (Equation 3) and short-run (Equation 4) equations relating TFP to R&D capital stock.

The derivation of TFP values utilized data obtained from the Singapore Department of Statistics (DOS) on the GDP, capital, and labor in Singapore for the years 1978 to 2012. GDP is expressed in real terms based on year 2000 prices. Physical capital was computed from annual data on gross fixed capital formation (GFCF) using the perpetual inventory method, assuming a depreciation rate of 5% per annum. Labor input is defined as the size of the national labor force, taken from the Ministry of Manpower Labor Force Survey.

Data on R&D expenditure were taken from the annual National R&D Survey conducted by the Agency for Science, Technology and Research (A*STAR). Using the stream of annual R&D expenditures from 1978 to 2012, the stock of R&D capital was constructed using the perpetual inventory approach as detailed by equation (4). A critical factor is the determination of the value of the stock in the initial period when t = 0, from which the inventory begins. We adopt a suggestion by Griliches (1980) that the initial stock of R&D capital, S_0, may be calculated as:

$$S_0 = R_0/(g + \delta)$$

Where:
R_0 = expenditure on R&D during the first year for which data value is available
g = the average annual logarithmic growth of R&D expenditure over the period for which published R&D data were available
δ = the depreciation rate of knowledge

In our analysis, the initial value of R&D expenditure at its inception in 1978 was S$66.1 million expressed in constant prices, with annual growth in R&D expenditure averaging 16.7% for the period 1978 to 2012. With the assumption of a 10% depreciation rate, the initial stock of R&D capital (in million S$) was therefore calculated as:

$$S_{1978} = 66.1 / (0.167 + 0.1) = 247.5$$

This initial value is used in the first iteration of the perpetual inventory equation (4) to calculate R&D capital stock for 1979. A 10% depreciation rate is assumed throughout the period 1978 to 2012.[1] The resulting values of R&D capital stock are charted in Figure 1.

To account for factor log (Z) in equation (2), data related to human capital development were obtained from the Ministry of Education. Annual data were collated for average years of schooling and annual government expenditure on education.

4. RESULTS

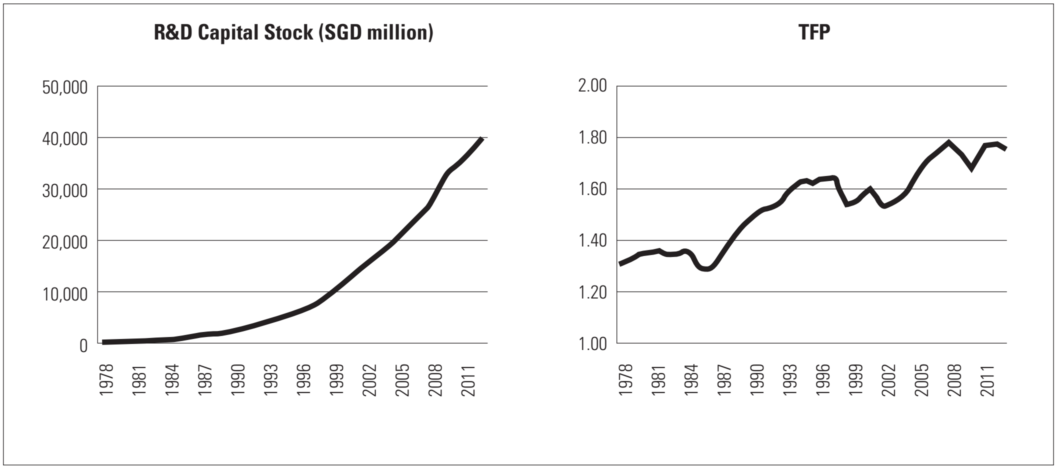
4.1. R&D Capital and TFP Trends in Singapore

Figure 1 shows the trends in the computed values of R&D capital stock and TFP. Singapore's R&D capital stock has followed an uptrend trend since 1978 with a beginning inventory value of S$247.5 million, reaching almost S$40 billion by 2012. Computed values for TFP also show a trend of steady increase over the years, with occasional disruptions to the upward trend in response to shocks from international events such as the Asian financial crisis in 1997 and the global finan-

[1] Nadiri (1993) noted that the depreciation rate to generate stock of R&D capital is often arbitrarily determined. Many empirical studies use depreciation rates of the order of 10 to 15 per cent per annum. Sensitivity analysis of the regression results with respect to different depreciation rates ranging between 10% and 20% was conducted. Results are found to be robust to different rates assumed.

cial crisis in 2008. After reaching a peak between 2007 and 2008, for example, TFP in Singapore declined following the global financial crisis but managed to climb back to the pre-crisis level by 2011.

FIGURE 1. Trend in Stock of R&D Capital and TFP in Singapore, 1978-2012



4.2. Long Run Relationship between R&D and Productivity

Augmented Dickey–Fuller (ADF) tests were conducted on TFP and log (*S*) and confirmed the existence of unit roots for both variables; in other words, the data are non-stationary. Having established the non-stationary nature of TFP and log (*S*), we proceed to determine if the two are co-integrated. Co-integration denotes a linear combination of non-stationary variables that yields a stationary series; establishing co-integration demonstrates that there is a long-run equilibrium relationship between the two variables.

Table 2 shows the results obtained from estimating Equation (2), without the inclusion of human development factors (denoted as log (*Z*)). An ADF unit root test (with intercept included) was conducted on the residuals obtained from estimating this equation. Results of the ADF test confirm the stationarity of the residuals and show that TFP and log (*S*) are co-integrated, and there is therefore a long-run equilibrium relationship between R&D capital stock and TFP.

When education-related factors are included in Equation (2) as control variables, the residuals were tested and found to be non-stationary, so we cannot proceed to estimate the error correction model of Equation (3). Consequently, log (*Z*) is not considered in our analysis.

Table 2. Testing Co-integration Between TFP and Log (S)

Equation: TFP = log $B + \gamma$ log S

Dependent Variable: TFP

Depreciation Rate for R&D Capital Stock = 10%

Sample: 1978–2012

Included observations: 35

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.786011	0.056152	13.99788	0.000
Log S (R&D Capital Stock)	0.090423	0.00656	13.78485	0.000

R-squared	0.852033	Mean (dependent var)	1.546848
Adjusted R-squared	0.847549	S.D. (dependent var)	0.156519
S.E. of regression	0.061113	Akaike info criterion	-2.696739
Sum squared residual s	0.123248	Schwarz criterion	-2.607862
Log likelihood	49.19293	Hannan-Quinn criterion	-2.666058
F-statistic	190.022	Durbin-Watson statistic	0.532836
Probability (F-statistic)	0.000		

Co-integration Test: Residuals from TFP = log $B + \gamma$log S

ADF t-statistic (with intercept)	-3.855801	1% Critical Value	-3.711457
Prob.	0.0071	5% Critical Value	-2.981038

Conclusion: Residuals are stationary, TFP and Log S are co-integrated

4.3. Impact of R&D on TFP

Having established a long-run co-integrated relationship, a short-run error correction model (ECM) was constructed, of the general ADL(x,y) form as shown in Equation (3). We began with an ADL model with a lag length of 3 and "tested-down" to a model ADL(1,0)[2] given by Equation (3a), with results reported in Table 3. The coefficients estimated form the basis of R&D impact calculation.

$$\text{TFP}_t = \beta + \lambda\, \text{TFP}_{t-1} + \gamma \log S_t \qquad (3a)$$

2 Sensitivity analysis was conducted with different lag structures. Results were found to be robust to changes in ADL structure.

TABLE 3. Short Run Error Correction Model

Equation: $TFP_t = \beta + \lambda\, TFP_{t-1} + \gamma \log S_t$

Dependent Variable: TFP_t

Method: Least Squares

Sample: 1979–2012

Included observations: 34

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.220588	0.097635	2.259301408	0.031
TFP_{t-1}	0.728219	0.11677	6.236351091	0.000
Log S_t (R&D Capital Stock)	0.024827	0.011724	2.117644552	0.042

R-squared	0.852033	Mean (dependent var)	1.546848
Adjusted R-squared	0.847549	S.D. (dependent var)	0.156519
S.E. of regression	0.061113	Akaike info criterion	-2.696739
Sum squared residuals	0.123248	Schwarz criterion	-2.607862
Log likelihood	49.19293	Hannan-Quinn criterion	-2.666058
F-statistic	190.022	Durbin-Watson statistic	0.532836
Probability (F-statistic)	0.000		

The estimated coefficients on Log S in Tables 2 and 3 are used to compute various indicators of the impact of R&D on TFP in Singapore. These indicators are summarized in Table 4. The elasticities estimated in the analysis need to be interpreted with care, as the dependent variable is TFP and not GDP. Following Guellec and van Pottelsberghe de la Potterie (2001), the direct impact of R&D on output is already captured in the TFP measure as it incorporates labor and capital devoted to R&D. As such, the positive elasticities signal the existence of spillovers and reflect the social return to R&D investment. From Table 4, it is evident that the long-run impact (elasticity of 0.091) of R&D on Singapore's TFP is almost four times as much as the short-run impact (elasticity of 0.025). This indicates that there is a significant lagged effect in the contribution of R&D to TFP.

The mean lag and median lag measure the speed at which TFP responds to changes in R&D capital stock. Shorter periods for the mean and median lag would indicate a faster adjustment process for TFP in response to changes in R&D capital. The internal rate of return (IRR) provides a measure of the profitability in investing resources in R&D. The IRR on R&D investment can be contrasted to the cost of borrowing funds as an indication of profitability of R&D projects.

From Table 4, the median lag or half-life of R&D investment is 2.19 years. In other words, it will take 2.19 years for half the effect from R&D to be realized in terms of TFP growth. The mean lag shows that on average, it takes 2.68 years for an increase in R&D capital stock to have an effect on GDP. As an indication of the magnitude of the impact, the internal rate of return computed over the last five years was 6.8%, while the longer-term IRR over 10 years is much higher at 20.8%. These rates of return compare against market rates of between 5 and 6 percent for bank loans and other sources of debt funding. R&D investment is profitable, especially in the long run, as it yields higher returns than the cost of funding.

TABLE 4. Impact of R&D Capital in Singapore

Parameter	Value
Long Run Elasticity of TFP with respect to R&D[3]	0.091
Short Run Elasticity of TFP with respect to R&D	0.025
Mean Lag, in years	2.68
Median Lag, in years	2.19
IRR (10 years)	20.8%
IRR (5 years)	6.8%

Table 5 summarizes comparable estimated parameters for Singapore vis-à-vis other countries for which equivalent studies have been done. The studies featured share a commonality in using national-level data to investigate the relationship between R&D and productivity. These studies also all adopt the Cobb-Douglas form for the production function equation, assuming constant return to scales and perfect competition, and compute TFP as the Solow residual. However, there are certain differences which should be borne in mind when comparing parameter estimates. The studies use different dependent variables, with Lichtenberg (1992) studying the impact of R&D on GDP per capita while the two studies using OECD samples examined Private sector TFP as the variable of interest. Several of the studies also augment the TFP equation with additional determinants other than R&D capital stock, such as unemployment rate (Guellec & van Pottelsberghe de la Potterie, 2001) and international trade (Coe & Helpman, 1995).

Table 5 also compares the findings for Singapore in this current paper with earlier findings in Ho, et al. (2009) which examined data up to 2001. We find that the estimated long term elasticities are at comparable levels in both studies. However, adding recent data from the last 10 years has the effect of increasing short-term elasticity and shortening the estimated adjustment period of GDP to changes in R&D capital. While R&D productivity appears to be unchanged in the long run, its "cycle time" to create economic impact has improved in recent years.

Our estimate for Singapore's long run elasticity (0.091) appears to be slightly higher than Lichtenberg's (1992) estimate of 0.068 to 0.077 for the elasticity of GDP with respect to private R&D, where the estimate is derived using cross-sectional data from 53 countries.[4] Similarly, the elasticity value for Singapore is slightly higher than Coe and Helpman's (1995) estimate of 0.078 for 14 non-

[3] The long run elasticity of TFP with respect to (wrt) S is given by $\gamma/(1-\lambda) = 0.0248/(1-0.7282) = 0.091$.

[4] These elasticities, however, are not completely comparable, as Lichtenberg's study uses GDP per capita as the dependent variable while R&D is measured in terms of flows of expenditure.

G7 OECD nations plus Israel, but still considerably lower than the 0.234 elasticity estimated for the G7 nations.

The computed value for Singapore's short-run elasticity of 0.025 is comparable with the estimated values of 0.024 for private R&D and 0.028 for public R&D across 16 OECD countries (Guellec & van Pottelsberghe de la Potterie, 2001). Singapore's long-run elasticity (0.091), however, is noted to be lower than the values of 16 OECD countries estimated by Guellec and van Pottelsberghe de la Potterie (2001) at 0.13 for private R&D and 0.17 for public R&D.

TABLE 5. Comparison of Parameter Estimates from Selected Studies

	Singapore (current paper)	Singapore (Ho et al., 2009)	Greece (Voutsinas & Tsamadias, 2014)	16 OECD Countries (Guellec & van Pottelsberghe de la Potterie, 2001)	53 countries (Lichtenberg, 1992)	22 OECD countries + Israel(Coe & Helpman, 1995)
Dependent Variable	TFP (based on GDP)	TFP (based on GDP)	TFP (based on GDP)	Private Sector TFP	Real GDP per capita	Private Sector TFP
Production Function	Cobb-Douglas	Cobb-Douglas	Cobb-Douglas	Cobb-Douglas	Cobb-Douglas	Cobb-Douglas
Data Structure	Time series, single economy	Time series, single economy	Time series, single economy	Panel data of time series in multiple economies	Panel data of time series in multiple economies	Panel data of time series in multiple economies
Measure of R&D	R&D stock	R&D stock	R&D stock	R&D stock	R&D expenditure	R&D stock
Period of Estimation	1978–2012	1978–2001	1987–2007	1980–1998	1985	1971–1990
PARAMETERS						
Lambda λ	0.728	0.837	0.039	0.82	N/A	N/A
Short-Run Elasticity with respect to R&D	0.025	0.013	Non-significant	0.024 (private R&D) 0.028 (public R&D)	N/A	N/A
Long-Run Elasticity with respect to R&D	0.091	0.081	0.038 (total R&D) 0.075 (public R&D)	0.13 (private R&D) 0.17 (public R&D)	0.068 to 0.077	0.078 (non-G7) 0.234 (G7)
Mean Lag	2.68	5.12	N/A	4.55	N/A	N/A
Median Lag	2.19	3.89	N/A	3.49	N/A	N/A

4.4. Testing Effect of Policy Changes

To determine if changes in policy have had an impact on the relationship between R&D and TFP, we search for any points at which there is a significant shift in the short-run elasticity of TFP with respect to R&D. We test for structural breaks, observed as unexpected shifts in the time series data which can occur as result of a "shock" to the equilibrium state.

A Chow Breakpoint Test was carried out to test for structural breaks in the year 2000 (comparing 1978–2000 versus 2001–2012), in 1995 (comparing 1978–1995 versus 1996–2012), and in 1990 (comparing 1978–1990 versus 1991–2012). These 3 points reflect times at which notable new policies and institutional changes were implemented with regards to S&T development in Singapore.

The presence of structural breaks would suggest that policy changes induced corresponding changes in R&D productivity.

The test for structural shifts is done by applying the Chow test to the ADL (1, 0) error correction model as represented by equation (4a). Table 6 shows the results from the Chow Breakpoint Test. We can conclude that the short-run elasticity of TFP with respect to R&D has not changed significantly over the years. The introduction of the national science and technology plans and the reorganization of NSTB as A*STAR are not associated with improved productivity of R&D in the short run.

TABLE 6. Chow Test for Structural Breaks

Chow Test applied to $TFP_t = \beta + \lambda_1 TFP_{t-1} + \gamma_t \log S_t$			
Break Point	F-statistic	Probability	Conclusion
2000 (A-STAR, BMRC, SERC established)	0.648582	0.5904	No break
1995 (2nd NSTP)	1.185012	0.3333	No break
1990 (1st NSTP, NSTB established)	0.268087	0.8478	No break

4.5. Testing Causality between Public & Private R&D Spending

Our third research question hypothesizes that increases in public sector R&D expenditure stimulate R&D activities in the private sector. The opposite direction of causality is not expected, as innovation in the private sector is usually protected for reasons of corporate competition, which restricts the flow into the public domain knowledge pool.

To test these hypotheses, we determine if there is causality between public and private R&D spending in Singapore. In particular, we expect significant unidirectional causality from public sector R&D stock to private sector R&D. To examine the causality patterns between public and private R&D, Granger Causality Tests were conducted in both directions.

(1) Public R&D causes Private R&D

$$\text{Log Pte\_}S_t = \alpha + \phi_1 \log \text{Pte\_}S_{t-1} + \ldots + \phi_x \log \text{Pte\_}S_{t-x} + \delta_1 \log \text{Pub\_}S_{t-1} + \ldots + \delta_x \log \text{Pub\_}S_{t-x}$$

(2) Private R&D causes Public R&D

$$\text{Log Pub\_}S_t = \alpha + \phi_1 \log \text{Pub\_}S_{t-1} + \ldots + \phi_x \log \text{Pub\_}S_{t-x} + \delta 1 \log\text{Pte\_}S_{t-1} + \ldots + \delta_x \log \text{Pte\_}S_{t-x}$$

Results are reported in Table 7. The findings confirm that an increase in public R&D capital stock in the previous year does have a significant and positive impact on private sector R&D capital stock in the current year. However, changes in private sector R&D did not result in an effect on public sector R&D. We can therefore conclude that public sector R&D contributes to increased private sector

R&D, with a one-year lag between cause and effect. On the other hand, R&D activities in the private sector do not have any causality effect on the level of R&D in the public sector.

TABLE 7. Causality between Public and Private R&D

Granger Causality Tests (H_0: $\sigma_1,\ldots,\sigma_x = 0$)			
	Coefficient	Significance	Conclusion
1) Dependent = **Private** R&D capital stock at time t			
$\text{Log Pte\_}S_t = \alpha + \phi_1 \log \text{Pte\_}S_{t-1} + \ldots + \phi_x \log \text{Pte\_}S_{t-x} + \delta_1 \log \text{Pub\_}S_{t-1} + \ldots + \delta_x \log \text{Pub\_}S_{t-x}$			
Constant	0.141*	0.067	Public R&D causes Private R&D
Private R&D at *t*-1	1.295***	0.000	
Private R&D at *t*-2	-0.399***	0.007	
Public R&D at *t*-1	0.270**	0.029	
Public R&D at *t*-2	-0.170	0.1907	
2) Dependent = **Public** R&D capital stock at time t			
$\text{Log Pub\_}S_t = \alpha + \phi_1 \log \text{Pub\_}S_{t-1} + \ldots + \phi_x \log \text{Pub\_}S_{t-x} + \delta_1 \log \text{Pte\_}S_{t-1} + \ldots + \delta_x \log \text{Pte\_}S_{t-x}$			
Constant	0.133**	0.028	Private R&D does not cause Public R&D
Public R&D at *t*-1	1.766***	0.000	
Public R&D at *t*-2	-0.809***	0.000	
Private R&D at *t*-1	-0.123	0.337	
Private R&D at *t*-2	0.154	0.157	

Note: Results are reported for VAR (2) structure. Findings were consistent when different lag structures were used.

5. DISCUSSIONS & POLICY IMPLICATION

This paper establishes a long-run equilibrium relationship between R&D capital and TFP in Singapore. This provides empirical verification of positive returns on R&D investment. Economic impact of R&D in the long run (elasticity = 0.091) is almost four times as much as the short run impact (elasticity = 0.025). The short-term productivity of R&D in Singapore is comparable to that of smaller advanced economies in the OECD. However, in terms of R&D productivity in the long term, Singapore lags behind the smaller OECD economies (with an estimated elasticity of 0.13–0.17) and the gap between Singapore and the G7 nations is even more considerable (with estimated elasticities of 0.091 and 0.234, respectively).

We suggest three explanatory factors with which the above findings can be interpreted. First, the nature of R&D activities in Singapore may differ from those in the OECD countries; it may be that R&D in Singapore is more downstream, or is being conducted in technology fields (e.g., information and communications technology or electronics) where the economic impact is limited to a shorter horizon. This is supported by the shorter mean and median lag values estimated for

Singapore compared to the OECD economies. Investments in new, science-based technological fields such as life sciences and advanced materials only began to intensify in the mid-2000s. The long-run impact may not yet be evident, as such fields typically require longer gestation periods for discoveries to be translated into economic value. Furthermore, the increased investments in these emerging areas have not thus far been matched by deepened capability to exploit basic research; few local firms at present have the absorptive capacity to commercialize discoveries in emerging fields. Given that our data stops at 2012, the findings here may not have captured more recent long-run impacts of recent R&D policy directions, such as those in the RIE2015 plan which address the capability of industry to exploit research outputs. The time-series analysis, in particular, should be revisited in the future when policies to boost absorptive capacity have been more widely implemented and more data points are available.

Another possible explanation for the comparatively lower productivity of R&D investment in Singapore is the proportionally lower level of private sector R&D activities compared to the advanced OECD nations. In his cross-country study, Lichtenberg (1992) suggested that the marginal product of government-funded R&D capital is much lower than that of private sector R&D capital. Countries with a higher government share in R&D spending exhibited significantly lower productivity growth than countries driven by private sector investment. In 2011, Singapore had 38% of the total R&D expenditure coming from government and higher education sectors, compared to an average of 30% in the OECD countries. In Appendix 1, we present preliminary findings of analysis comparing elasticity estimates for TFP with respect to private versus public R&D in Singapore. The findings suggest that private R&D does have a higher and more immediate direct impact than public R&D.

Last, but not least, the gap between Singapore and the large G7 nations may be related to the issue of "leakage" of value capture. This challenge is common to other small advanced economies, and arises from the relatively small size of the domestic economy. The domestic economy faces fierce competition from other economies to capture the chain of downstream values that the R&D results could potentially create. Porter (1990) suggests that a nation needs to have unique factors or resource advantages, strong demand conditions, related and supporting industry infrastructures, and competitive markets to retain the value that it creates. Lepak, Smith, and Taylor (2007) frame these conditions as isolating mechanisms that allow for value to be captured, with the absence of such mechanisms leading to leakage or slippage of value capture. With all other things being equal, mechanisms to retain value and prevent leakage are typically less effective in small economies due to weaker demand conditions in the local market and limited local capability (Porter, 1990). In the case of Singapore, value capture leakage is likely to be exacerbated by the high share of R&D being done by subsidiaries of foreign multinational corporations (MNCs). Multinational corporations have consistently accounted for over 50% of private sector R&D spending in Singapore, rising to over 65% since the mid-2000s. Compared to indigenous firms, foreign MNCs are likely to have more options for their business and a higher propensity to exploit their R&D results elsewhere. They might conduct new product development at their foreign corporate headquarters or manufacture products in a lower cost location than Singapore, for example.

Our findings suggest that the quantitative impact of R&D in Singapore has not changed significantly in the last 30 years. Policy shifts in the 1990s to 2000 failed to induce structural breaks to raise the short-term productivity of R&D. Preliminary comparative analysis on the returns on public and private R&D (reported in Appendix 1) further revealed that private R&D in Singapore has had a greater and more immediate impact on TFP compared to public R&D. These findings should not be seen as an argument against public R&D investment, for several reasons. Singapore's policy has been to focus public R&D resources in cutting-edge technologies, in order to create competitive advantage in emerging sectors. R&D spending is therefore part of a broader long-term strategy to develop knowledge-intensive clusters in Singapore. The full economic impact of this spending will only be evident in the future when the clusters have matured and there is a critical mass of private sector innovators to create value from research findings. Secondly, public-funded R&D plays an important role in seeding the national innovation system with new knowledge that may be exploited commercially. Causality analysis shows that public R&D generates positive externalities, which in turn stimulate R&D activity in the private sector and augment private R&D capital stock in Singapore. This affirms the multiplier effect of public science.

The empirical findings in this paper suggest several policy implications for increasing the economic impact of R&D investment in Singapore. First, public sector R&D is known to stimulate private sector R&D. Policies should therefore be developed to facilitate increased technology transfer from the public to the private sector in order to maximize the positive externalities of public research. Such policies could have a micro-targeted scope, such as incentives for companies to license in technologies from public research institutes (PRIs) and universities, and incentives to the latter to encourage technology commercialization through the formation of spin-offs. These policies could also encompass macro-level initiatives to create a conducive environment for technology transfer, such as fostering a vibrant entrepreneurship support ecosystem with ready venture financing and incubation support, or growing infrastructure for translational research and applied development to translate public R&D into market-ready applications that can be more easily adopted by industry.

Secondly, our findings suggest the need to increase the absorptive capacity of indigenous firms in Singapore by assisting local SMEs to adopt new processes or upgrade technology. The existing programs can be refined and extended to emphasize absorptive capacity through expertise to channel externally-sourced R&D into innovative products and services. For example, the T-UP program administered by A*STAR has improved aspects of absorptive capacity such as technology learning and enterprise innovation by seconding selected R&D personnel from PRIs to work in local SMEs for up to two years (Ho, Hang, Ruan, & Wong, 2016). This program could be expanded in scope, and additional strategies to promote open innovation should be considered to raise the absorptive capacity of local firms. The success of Taiwan's Industrial Technology Research Institute in facilitating technology absorption capacity of indigenous Taiwanese firms could serve as a valuable model (see e.g., Hu & Matthews, 2005).

Finally, policies can minimize the leakage of value capture by promoting greater retention of the downstream value creation activities arising from R&D investments within Singapore. This leakage may explain the relatively lower long-run productivity of R&D in Singapore when compared to the OECD nations, especially the large G7 economies. Given the dominance of foreign firms in Singapore's private sector R&D, an obvious priority is increasing the localization of value capturing activities of foreign firms. In particular, value capturing activities pertaining to Intellectual Property (IP) as the most tangible outcome of R&D should be emphasized. Current taxation-based incentives offer concessionary rates for royalties and income derived from IP licensing or transactions; the government could provide tax relief on income derived from qualifying patents or other forms of IP through a broad-based scheme like a "Patent Box" or "Innovation Box." Patent Boxes been recently introduced across Europe as well as in China, and is currently being considered in the USA as well. A Patent Box is advantageous compared with traditional R&D grants in that it provides firms with an incentive to go beyond just conducting R&D to commercialize and capture the value created by their R&D efforts.

Beyond this, value capture can be increased by positioning Singapore as a regional hub for IP management and intermediary services, in order to achieve scale and to diversify IP capture activities. The recent Singapore IP Hub Masterplan outlines a series of recommended strategies to realize this vision (Intellectual Property Office of Singapore, 2013). A critical mass of IP expertise and transactions would not only increase value retention, but may also create additional value from domestic R&D investment. A hub strategy would also increase localized value capture by foreign firms in Singapore. There are large potential markets in ASEAN (the Association of Southeast Asian Nations) and the broader Asian region for IP assets created from R&D conducted in Singapore. As a regional IP hub, Singapore is well-positioned to be a base for foreign firms to reach these markets, locating their regional marketing efforts here and therefore localizing the value captured.

Our findings for Singapore have relevant policy implications for other NIEs. Simply increasing public R&D expenditure is insufficient, as public sector share of total R&D in most developing countries is already much higher than in the OECD. The critical factor to increase R&D impact is not more expenditure, but raising the technological absorption capacity of local firms. SMEs in particular lack both the scale to invest heavily in their own R&D and the absorptive capacity to commercialize public R&D. The role of industrial policy is critical in this regard to promote development of local firms and set direction for prioritization of public R&D to support key industrial sectors. Secondly, the experience of Singapore underlines the challenge of "leakage" of value capture for NIEs that are limited by lack of scale and a weak supporting innovation ecosystem. In particular, innovation intermediaries that can increase value capture (such as technology translation institutions and IP services firms) are often insufficiently developed. As such, proactive policies are needed to facilitate the establishment of such innovation infrastructure and institutions.

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APPENDIX 1: Comparing the Impact of Public versus Private Sector R&D on TFP

The findings in this Annex are presented with two important caveats. Firstly, the data do not fulfil the requirement of unit root at the levels for the variables in the co-integration equation. The time series for public sector R&D capital stock (in log form) is in fact stationary. As such, the co-integration equation is subject to misspecification. Secondly, elasticity estimates reported are not robust to changes in the lag structure of the TFP error correction model equation. In addition, private and public R&D capital stock are highly correlated, so inclusion of both series as determinants introduced multicollinearity. The resulting estimates for predictors are therefore subject to imprecision.

We begin by constructing the long-run TFP equation to be estimated, following the specification used by Guellec and van Pottelsberghe de la Potterie (2001), which similarly attempted to subdivide R&D capital into constituent components including private and public sector R&D.

$$\text{TFP} = \log B + \gamma_{pte} \log \text{Pte\_}S + \gamma_{pub} \log \text{Pub\_}S \qquad (3b)$$

We conducted ADF unit root tests on the variables log (Pte_*S*) and log (Pub_*S*) to determine if both time series are non-stationary. The results show that log (Pte_*S*) is non-stationary; however, log (Pub_*S*) is stationary, hence violating the requirement of non-stationary variables in the long-run equation. As we proceed to the next step to test for co-integration in the TFP equation (3b), the results should be interpreted with this caveat in mind.

A unit root test was conducted on the residuals from estimating equation 3b to determine if TFP, log (Pte_*S*) and log (Pub_*S*) are co-integrated. The results obtained show that the residuals are weakly stationary, with the null hypothesis of unit-roots rejected only in the case of the ADF test without intercepts. As such, the evidence only supports a tentative suggestion of co-integration, i.e., that there is a long-run equilibrium relationship between TFP and public and private R&D capital stock.

Similar to before, a short-run error correction model was constructed of the general ADL(x,y) form. The ADL (1,0) structure used for estimating elasticity of total R&D was not a good fit and we adopted an ADL (1, 1) structure instead.

Table A1 summarizes the impact of public and private R&D capital investments on TFP. When comparing the public and private sectors, private R&D is noted to have a higher TFP elasticity with respect to R&D in both the short and long run. As such, private R&D capital stock appears to be more productive than public R&D capital stock. Changes in private R&D capital also have more immediate impact on TFP compared to public R&D. On average, it takes 1.3 years for an increase in private R&D capital to have an impact on GDP, while the average adjustment period is approximately twice as long (2.7 years)for public R&D. It takes 1.24 years for half the effect from increased private R&D to be realized in terms of GDP growth, while the half-life of public sector R&D is more than double that at 3.21 years. This suggests that the impact of public R&D may be concentrated more towards the later years.

As an indication of the magnitude of the impact, the internal rate of return computed over the five- and ten-year periods were estimated. Public R&D is noted to have a higher internal rate of return than private R&D, likely due in part to the lower expenditure outlays in the public sector.

TABLE A1. Summary of Parameter Estimates and Computed Indicators

	Total R&D Capital Stock	Private R&D capital stock	Public R&D capital stock
Long Run Elasticity of TFP wrt R&D	0.091	0.055	0.035
Short Run Elasticity of TFP wrt R&D	0.025	0.016	0.010
Mean Lag, in years	2.68	1.27	2.69
Median Lag, in years	2.19	1.24	3.21
Internal Rate of Return (10 years)	20.8%	21.1%	23.8%
Internal Rate of Return (5 years)	6.8%	5.9%	12.5%