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Interaction in R&D and the Case-by-Case Subsidy Rule

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Abstract

This paper studies the performance of government subsidy programs which fund business R&D projects. A commonly used criterion for distributing funding is the case-by-case (CbC) rule. Under the rule, project funding is decided based on the gap between a project's social and private return. This paper finds that in the presence of pervasive complementarity in R&D activites CbC funding is socially excessive. On the other hand, in the presence of pervasive substitutability in R&D activities CbC funding is socially insufficient. Since the situation can differ greatly from one industry to the next, these findings suggest governments may be over-funding research in some industries at the expense of research in other under-funded industries.

JEL Classification: H40; O31; O38; O30
Keywords: R&D Subsidies; Interaction in R&D; Case-by-Case Subsidy Rule; Welfare

1 Introduction

Are governments over-funding or under-funding research in specific industries? Important examples might include aerospace, computers, defence, electronics equipment, energy, pharmaceuticals, the arts and telecommunications. This paper suggests governments may be over-funding research in industries in which innovations tend to be complementary and under-funding research in industries in which innovations tend to be substitutable.

The paper also suggests a set of industry characteristics useful for identifying a funding problem. Over-funding is likely to occur in industries characterized by

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high knowledge spillovers, weak product market rivalry and a plentiful supply of R&D inputs. On the other hand, under-funding is likely to occur in industries characterized by weak knowledge spillovers, intense product market rivalry and an inelastic supply of R&D inputs.

Governments spend a considerable amount of resources funding business R&D.[1] In 2005, public support amounted to $35 billion in OECD countries.[2] The main justification behind this support lies in the mass of evidence, both theoretical and empirical, that, in the absence of intervention, firms under-invest in R&D due to the existence of R&D spillovers (Arrow, 1962; Nelson, 1959; Griliches, 1992). The government's objective of funding R&D to a socially desirable level is complicated by the possibility that subsidies may displace, i.e. crowd-out or stimulate, privately-funded R&D (David et al., 2000; Klette et al., 2000).[3]

The case-by-case (CbC) subsidy rule suggests that the path through this dilemma is to determine funding based on a project's spillover gap (Jaffe, 1996). This spillover gap is the difference between a project's social and private return. The argument is that by focusing funding on projects with large spillover gaps, the agency can "minimise displacement by maximising the spillover gap" (Jaffe, 1996). A large spillover gap might signal the possiblity that social returns are high at the same time that the risk of displacement is low. An important feature of this rule is it ignores possible indirect effects of subsidies on R&D which may arise due to interaction between firms in R&D decisions.[4]

In general, the relationship between the R&D decisions of firms may be neutral, complementary or substitutative. Empirical evidence regarding the relationship between own and other's R&D suggests R&D complementarities between firms are important in many cases (Jaffe, 1986; Cohen and Levinthal, (1993); Geroski et al., 1993; Branstetter and Sakaibara, (1998)). Bernstein (1988) finds a complementary relationship in R&D intensive industries. On the other hand, Bernstein finds a substitutative relationship in industries with

[1] The majority of government programs which fund business R&D have a similar form: firms apply for project funding and the agency then decides how much to fund each project. The programs generally encompass a wide range of firms in diverse technology areas. Examples of such programs include ANVAR, SBIR, TIP. See Serrano-Velarde (2008) for a nice description of the ANVAR program.

[2] This represents one-fifth of government R&D spending and 7% of business R&D spending (OECD, 2007).

[3] If the agency subsidises a project with a high social return but in doing so stimulates (crowds-out) privately-financed R&D then the publicly funded level of investment will be socially excessive (insufficient) relative to the socially optimal level of investment. For example, suppose a project's laissez faire and socially optimal R&D spending are $30m and $50m respectively (m denotes million). Suppose the government subsidy is $20m. If publicy funded R&D is $60m ($45m) then the subsidy stimulated (crowds-out) privately financed R&D by $10m ($5m) implying that publicly funded R&D is socially excessive (insufficient).

[4] The term case-by-case rule is intended to emphasize that, under the rule, government intervention takes the form of a set of independent funding decisions based on a case by case evaluation of project returns.

moderate R&D spending. Popp (2009) finds that in the energy industry, innovation in clean energy technologies tends to substitute for R&D in dirty energy technologies.

This paper studies a two-stage game in order to investigate the performance of CbC funding in the presence of interaction in R&D. In the first stage, government announces an R&D subsidy for each firm. These subsidies are calculated using the CbC rule. In the second stage, firms invest in R&D. Interaction in R&D is taken to be exogenous.

The main results are that in the absence of interaction in R&D, CbC funding implements social optimum R&D. However, if R&D complementarity (substitutablity) pervades the industry then subsidies stimulate (crowd-out) privately-financed R&D and CbC funding is socially excessive (insufficient).

In order to endogenise interaction in R&D, a third stage in which firms compete in the product market is added to the model's set up. This stage incorporates a number of distinct channels, suggested by the literature, through which R&D by one firm might influence the innovation incentives of other firms: knowledge spillovers (Levin and Reiss, 1985; Levin, 1988),[5] R&D input markets, e.g. an inelastic supply of R&D personnel (Goolsbee, 1998),[6] business stealing effects arising from product market rivaly between firms (Bloom et al., 2007).[7]

The main results reveal a close relationship between the direction of the CbC funding problem and an industry's location in knowledge spillover-product rivalry space. Under the CbC rule, over-funding occurs in industries in which knowledge spillovers dominate product rivalry. On the other hand, under-funding occurs in industries in which product rivalry dominates knowledge spillovers. Allowing for interactions in R&D costs reveals that, when knowledge spillovers dominate (are balanced by) product rivalry, an inelastic supply of R&D inputs can remove (create) a CbC over-funding (under-funding) problem.

The article contributes to the literature on government rules of thumb for subsidizing business R&D (Adam Jaffe 1996, 2002). The convention in this

[5] For example, knowledge spillovers may influence the investment incentives of receiving firms (Bernstein, 1988).

[6] The majority of R&D spending is actually salary payments for R&D workers. If the supply of scientific and engineering talent is quite inelastic then the impact of an increase in a firm's R&D spending on the hiring costs of R&D personnel can effect the R&D behaviour of other firms.

[7] One of the primary motivations for firms to invest in R&D is to gain competitive advantate vis-a-vis their rivals (Branden and Spencer, 1983). Interaction in R&D can arise because of the interplay between innovation and market structure. On the one hand, firm incentives to innovate depend on the intensity of competition in the product market, e.g number of rivals, industry concentration, degree of product substitutability, nature of competition (Arrow, 1962). On the other hand, innovation shapes market structure thereby influencing investment incentives, e.g. when R&D increases market share or keeps potential competition at bay (Gilbert et al., 1982).

literature has been to abstract from interactions between firms in R&D decisions. This paper suggests ignoring such interactions results in over-funding of research in the presence of pervasive R&D complementarity and under-funding of research in the presence of pervasive R&D substitubility.

The model of this paper is likely to be useful for interpreting some of the mixed econometric evidence on the effectiveness of public support to business R&D (see surveys by David et al. (2000) and Klette et al. (2000)). For example, Branstetter and Sakakibara (1998) study Japanese government funded research consortia and find evidence that participation in these consortia stimulated private R&D spending. Funding was concentrated in a few high-tech industries such as computers/semiconductors and telecommunications. In addition, the government heavily subsidized participating firms, covering on average two-thirds of a project's research cost. Branstetter and Sakakibara argue that government generally sought to bring together firms with complementary research assets. The apparent success of this program inspired similar programs in other countries e.g SEMATECH. This paper dampens such optimism suggesting the Japanese government may have over-funded research in these technology areas.

In another example, Goolsbee (1998) claims an inelastic supply of scientists and engineers poses a serious problem for government efforts to increase inventive activity via subsidies. Goolsbee finds evidence that government R&D spending significantly increase the wages of R&D personnel implying government funding directly crowds-out private inventive activity. This paper suggests an inelastic supply of R&D inputs can have positive welfare implications, removing a CbC over-funding problem in the presence R&D complementarity. A similar point was made in the work of David and Hall (2000) who argue crowding out in the short run, stemming from an inelastic supply of R&D workers, can be offset in the long run by increased knowledge spillovers.

The paper also contributes to the growing literature on the different impacts of innovation across industries based on knowledge spillover-product rivalry industry characteristics, recently highlighted by McGahan and Silverman (2006) and Bloom et al. (2007). In addition to the different innovation impacts, this paper provides theoretical evidence that the performance of R&D subsidies differs across industries depending on knowledge spillover-product rivalry industry characteristics.

2 Exogenous Interaction in R&D

Consider an industry consisting of n firms. Each firm $i = 1, ..n$ chooses R&D effort $x_i \geq 0$, given the subsidy, s_i, it receives from government. The interdependent, bilinear R&D payoffs of the firms are given by

$$\pi_i(x_1, ..x_n) = \alpha x_i - \frac{1}{2}\sigma_I x_i^2 + \sum_{j \neq i} \sigma_C x_i x_j + s_i x_i, \text{ for } i = 1, .., n$$

in which $\alpha > 0$, $\sigma_I > 0$ and σ_C are exogenously given constants.[8] Interaction in R&D is captured by the cross derivative $\frac{\partial^2 \pi_i}{\partial x_i \partial x_j} = \sigma_C$, for all $i \neq j$, which can be of either sign. This cross derivative measures the change in firm i's incentive to innovate due to a marginal increase in firm j's R&D effort. When $\sigma_{\dot{C}} > 0$, the R&D efforts of firms are strategic complements and R&D complementarity is said to be pervasive in the industry. When $\sigma_C < 0$, the R&D efforts of firms are strategic substitutes and R&D substitutablity is said to be pervasive in the industry. The restriction, $\sigma_I > (n-1)\sigma_C$, ensures the existence of a unique interior Nash equilibrium denoted by $x^* = (x_1^*, .., x_n^*)$.

It is assumed that in the absence of intervention firms under-invest in R&D. Formally, suppose social welfare is defined as the sum of industry profits and social benefits arising from R&D spillovers to consumers and other firms outside the industry,[9]

$$W(x_1, .., x_n) = \sum_i \pi_i(x_1, .., x_n) + B(\sum_i x_i)$$

in which $B > 0$ measures the value of these external social benefits. Denote by $x^{**} = (x_1^{**}, .., x_n^{**})$ the social optimum R&D profile associated with W and denote by $\widehat{x} := x^* \mid_{(s_1,..,s_n)=0}$ the laissez-faire equilibrium R&D profile. Then, the investment gap of firm i, denoted Δ_i, is defined as the difference between the socially desirable and laissez faire R&D effort of the firm and must satisfy

$$\Delta_i := x_i^{**} - \widehat{x}_i > 0, \text{ for all } i = 1, .., n.$$ [10]

Government calculates subsidies under the CbC rule. Denote by s_i^{CbC} the CbC subsidy to firm i. It is assumed government knows the investment gap associated with each firms R&D activity and correctly anticipates the direct effect of a subsidy on the recipient firm's R&D, denoted by $d_i^*(s_i)$. Given Δ_i and $d_i^*(s_i)$, government chooses s_i^{CbC} in order to close the firm's investment gap, i.e.

$$\Delta_i = d_i^*(s_i^{CbC}), \text{ for all } i = 1, .., n$$

Notice that intervention takes the form of n independent subsidy decisions, one for each firm, and government ignores possible indirect subsidy effects that may arise from interaction in R&D.[11]

[8] This specification is a special case of the payoff functions presented in Ballester et al. (2006) in their research on peer effects.

[9] The model assumes R&D spillovers to firms outside the industry do not influence their R&D decisions. For example, innovations in computer software can significantly improve the productivity and hence profitablity of other firms without influencing their R&D decisions.

[10] Note that in the presence of R&D substitutablity, the investment gap is strictly positive provided external social benefits are sufficiently large, i.e. when $\sigma_C < 0$, the restriction $B > -\frac{(n-1)\sigma_C}{\sigma_I - (n-1)\sigma_C}$ ensures $\Delta_i > 0$, for all $i = 1, ..n$.

[11] The CbC formulation of the government subsidy decision is equivalent to choosing a subsidy program, $s^{CbC} = (s_1^{CbC}, .., s_n^{CbC})$, which maximises social welfare, W, anticipating $(d_i^*(s_i))_i$, i.e. $s^{CbC} = \arg \max_{(s_1,..,s_n)} W(\widehat{x}_1 + d_1^*(s_1), .., \widehat{x}_n + d_n^*(s_n))$.

2.1 Analysis and Results

The game is solved using backward induction. In the final stage, each firm chooses R&D effort to maximise its payoff given the R&D efforts of rival firms and the subsidy it receives from government. The first order condition is given by

$$\frac{\partial \pi_i}{\partial x_i} = \alpha + s_i - \sigma_I x_i + \sum_{j \neq i} \sigma_C x_j = 0$$

Rearranging terms, the best response function of firm i is

$$b_i((x_j)_{j \neq i}, s_i) = \frac{1}{\sigma_I}\alpha + \frac{1}{\sigma_I} s_i + \sum_{j \neq i} \frac{\sigma_C}{\sigma_I} x_j$$

Applying the implict function theorem to this system of equations, there exists n differentiable implicit functions $\{x_i(s_1, ..s_n)\}_i$ such that equilibrium industry R&D can be written as

$$\sum_i x_i^* = \sum_i b_i(s_i, (x_j(s_1, .., s_n))_{j \neq i})$$

Totally differentiating this expression with respect to s_i, around $(x_1^*, .., x_n^*)$, decomposes the impact of a subsidy on R&D into a direct and indirect effect,

$$\frac{d \sum x_j^*}{d s_i} = \underbrace{\frac{\partial b_i}{\partial s_i}}_{\textit{direct effect}(D_i)} + \underbrace{(\sum_{j \neq i} \underbrace{\frac{\partial b_i}{\partial x_j} \frac{\partial x_j}{\partial s_i}}_{\textit{feedback effect}(F_{ij})} + \sum_{j \neq i} (\underbrace{\sum_{l \neq j} \frac{\partial b_j}{\partial x_l} \frac{\partial x_l}{\partial s_i})}_{\textit{cross effect}(C_{ij})}}_{\textit{indirect effect}}$$

The indirect effect of a subsidy on R&D consists of $(n-1)$ feedback and cross effects. The cross effect, denoted C_{ij}, is the change in a rival firm's R&D stemming from the impact of the subsidy on R&D by other firms. The feedback effect, denoted F_{ij}, is the resulting influence on the recipient firm's R&D induced by this change in the rival firm's R&D. The direct effect of subsidy on R&D, denoted D_i, is the effect of the subsidy on the recipient firm's R&D abstracting from R&D interactions between recipient and rival firms. This direct effect can be computed from the firm's best response function and is given by $D_i = \frac{\partial b_i}{\partial s_i} = \frac{1}{\sigma_I}$.

Solving the system of equations and applying this decomposition,[12] equilibrium R&D given subsidy policy can be written as

$$x_i^*(s_1, .., s_n) = (\widehat{x}_i + \sum_{j \neq i} F_{ij} s_i + \sum_{j \neq i} C_{ij} s_j) + D_i s_i$$

[12] See the Appendix for the derivation of this equilibrium R&D expression.

in which $F_{ij} = \frac{\sigma_C^2}{\sigma_I A}$, $C_{ij} = \frac{\sigma_C}{A}$ and $D_i = \frac{1}{\sigma_I}$ are respectively the feedback, cross and direct effects and $A > 0$.[13] Since $F_{ij} \geq 0$, the feedback effect is positive irrespective of the nature of interaction in R&D. Thus, receiving a subsidy stimulates privately-financed R&D of the recipient firm. Notice that the sign of the cross effect depends on the nature of R&D interaction. If $\sigma_C > 0$ then $C_{ij} > 0$; hence in the presence of R&D complementarity, a subsidy to firm j stimulates firm i's R&D. If $\sigma_C < 0$ then $C_{ij} < 0$; hence in the presence of R&D substitutablity, a subsidy to firm j crowds-out firm i's R&D.

Invoking symmetry, equilibrium R&D given subsidy policy is

$$\underbrace{x^*(s)}_{\textit{publicly-funded R\&D}} = \underbrace{\widehat{x} + (n-1)(F+C)s}_{\textit{privately-financed}} + \underbrace{Ds}_{\textit{publicly-financed}}$$

Notice that, subsidy intervention in the presence of R&D complementarities implies privately financed R&D exceeds laissez-faire R&D.[14] On the other hand, subsidy intervention in the presence of R&D substitutablity implies laissez-faire R&D exceeds privately financed R&D.[15] These observations give the following result:

Proposition 1 *If R&D complementarity (substitutablity) is pervasive then government subsidy stimulates (crowds-out) privately-financed R&D.*

In the first stage, subsidies are calculated under the CbC rule. Government sets the subsidy equal to the investment gap anticipating the direct effect of the subsidy on R&D, i.e. $Ds^{CbC} = \Delta$. Substituting in for the direct effect reveals that the CbC subsidy is given by

$$s^{CbC} = \sigma_I \Delta$$

Notice that $s^{CbC} > 0$. The optimal subsidy, denoted by s^*, equates social optimum R&D and publicly funded R&D, i.e. $x^{**} = x^*(s^*)$. Simple calculations reveal the optimal subsidy is given by $s^* = \sigma_I \Delta - (n-1)\sigma_C \Delta$.[16] Notice that $s^* > 0$.[17] The CbC funding problem then is the difference between the CbC subsidy and the optimal subsidy and is given by

$$s^{CbC} - s^* = (n-1)\sigma_C \Delta$$

[13] Note that $A = (\sigma_I + \sigma_C)(\sigma_I - (n-1)\sigma_C) > 0$ since $\sigma_I > (n-1)\sigma_C$ by assumption. The term $\widehat{x}_i$ denotes the firm's laissez faire R&D effort and is given by $\widehat{x}_i = \frac{\sigma_I + \sigma_C}{A}\alpha$.

[14] Note that if $s > 0$ and $\sigma_C > 0$ then $F + C > 0$ and privately-financed R&D exceeds laissez-faire R&D, i.e. $\widehat{x} + (n-1)(F+C)s > \widehat{x}$.

[15] Note that if $s > 0$ and $\sigma_C < 0$ then $\sigma_I > \sigma_C$ implies $F + C < 0$ and laissez-faire R&D exceeds privately financed R&D, i.e. $\widehat{x} > \widehat{x} + (n-1)(F+C)s$.

[16] See the Appendix for the derivation of the optimal subsidy.

[17] The equilibrium restriction $\sigma_I > (n-1)\sigma_C$ and the under-investment assumption $\Delta > 0$ ensure $s^* > 0$.

The CbC funding problem is proportional to the investment gap, weighted by the extent of interaction in R&D across the industry. In the benchmark case, the situation in which there is no interaction in R&D, $\sigma_C = 0$, CbC funding is socially optimal, $s^{CbC} = s^*$.

Proposition 2 *In the absence of interaction in R&D, CbC funding is socially optimal.*

Since the investment gap is positive $\Delta > 0$, the direction of the CbC funding problem depends on the nature of interaction in R&D. If $\sigma_C > 0$ then $s^{CbC} > s^*$; hence when R&D complementarity pervades the industry, government over-subsidizes firms under the CbC rule. On the other hand, if $\sigma_C < 0$ then $s^{CbC} < s^*$; hence when R&D substituablity pervades the industry, government under-subsidizes firms under the CbC rule.[18]

Proposition 3 *If R&D complementarity (substitutablity) is pervasive then CbC funding is socially excessive (insufficient).*

The intuition for the result is as follows: if R&D complementarity (substitutablity) pervades the industry then, under the CbC rule, government does not internalise that subsidizing a firm stimulates (crowds-out) investment by rival firms thereby reducing (widening) the investment gap associated with their R&D activities. When government moves to decide funding for one of these rival firms, it does not take into account that the rival's investment gap is now smaller (larger). As a result, government over-subsidizes (under-subsidizes) the rival firm. Since, it does this for all firms in the industry, it is quite intuitive that government over-funds (under-funds) research under the rule.

Recall the social welfare function, $W = \sum_i \pi_i(x_1, .., x_n) + B(\sum_i x_i)$, presented earlier. The investment gap associated with W is given by

$$\Delta = \frac{B}{(\sigma_I - 2(n-1)\sigma_C)} + \frac{(n-1)\sigma_C}{(\sigma_I - (n-1)\sigma_C)(\sigma_I - 2(n-1)\sigma_C))}\alpha$$

First, notice that $\frac{\partial \Delta}{\partial B} > 0$ implies $\frac{\partial (s^{CbC} - s^*)}{\partial B} > 0$.[19] Hence, in the presence of interaction in R&D, the magnitude of the funding problem is increasing in the extent of external social benefits.

Second, holding constant the intensity of interaction in R&D, the magnitude of the CbC funding problem is smaller in the presence of R&D substitutablity than in the presence of R&D complementarity. Notice that $\frac{\partial \Delta}{\partial \sigma_C} > 0$; hence complementarity (substituablity) in R&D widens (reduces) the investment gap.

[18] Notice that, if $\Delta < 0$ then government over-taxes when complementarity in effort is pervasive and under-taxes when substituablity in effort is pervasive.

[19] See the Appendix for the derivation of this investment gap and results concerning the comparative static properties of the CbC funding problem.

Third, if $\sigma_C > 0$ then $\frac{\partial(s^{CbC}-s^*)}{\partial\sigma_C} > 0$; hence the magnitude of CbC over-funding is increasing in the intensity of R&D complementarity. On the other hand, if $\sigma_C < 0$ then $\frac{\partial(s^{CbC}-s^*)}{\partial\sigma_C} > 0$ provided B is sufficiently large; hence the magnitude CbC under-funding is increasing in the intensity of R&D substitutablity provided external social benefits are sufficiently large. Otherwise, stronger R&D substitutablity reduces CbC under-funding.

3 Endogenous Interaction in R&D

A third stage in which firms compete in the product market is added to the model set-up of the previous section and reduced-form R&D payoff functions are derived.

Firms compete in a symmetric differentiated-good Cournot oligopoly (the case of no product differentiation is a special case). Each firm sets output, q_i, and faces a linear inverse demand function $p_i(q_1,..,q_n)$ given by

$$p_i(q_1,..,q_n) = a - q_i - \delta(\textstyle\sum_{j\neq i} q_j)$$

in which $a > 0$ and $0 \leq \delta \leq 1$. The parameter δ is the degree of symmetric product differentiation. If $\delta = 0$ then the products are independent products and the firms behave as independent monopolists. If $\delta = 1$ then the products are perfect substitutes and the firms compete in a homogenous-product oligopoly.[20] The parameter δ measures the intensity of product market rivalry in the industry.

R&D, x_i, delivers a process innovation which reduces marginal production costs. These costs are linear and given by

$$c_i(x_1,..,x_n) = c - x_i - \beta(\textstyle\sum_{j\neq i} x_j)$$

with $a > c \geq x_i + \beta x_j \geq 0$ and $0 \leq \beta \leq 1$. The parameter β is the degree of symmetric knowledge spillover among the firms. This spillover implies some or all of the benefits of each firm's R&D flow without payment to rival firms. If $\beta = 1$ then the spillover is perfect. If $\beta = 0$ then there is no knowledge leakage.

R&D subsidies, s_i, lower the effective cost of R&D. This effective cost is given by

$$y(x_i, s_i) = -s_i x_i + \tfrac{1}{2}\psi x_i^2$$

with $\psi > 0$. Notice that the subsidy reduces the intercept term on the firm's marginal cost of R&D.

[20] This formulation of the inverse demand functions is taken from Yi (1997).

Bringing together expressions, firm profits are $\pi_i = p_i(q_i, q_j)q_i - c(x_i, x_j) - y(s_i, x_i)$. As in the previous section, it is assumed that in the absence of intervention each firm under-invests in R&D, i.e. $\Delta_i > 0$, for $i = 1, .., n$.[21]

Computing the Nash equilibrium outputs of the production stage, deriving the reduced-form R&D payoff functions and taking the first order condition gives,[22]

$$\frac{\partial \pi_i}{\partial x_i} = \alpha + s_i - \sigma_I x_i + \sum_{j \neq i} \sigma_C x_j = 0$$

in which

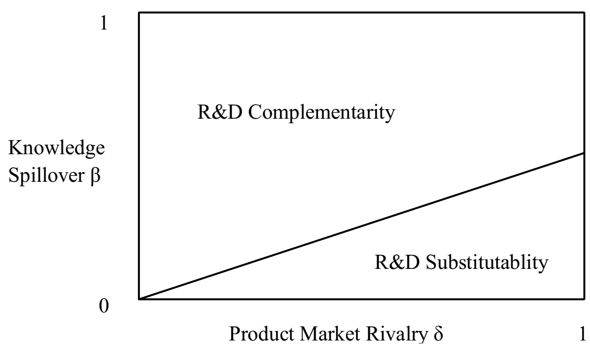
$$\alpha = \frac{2(2-\delta)(2-\delta+\delta(1-\beta)(n-1))(a-c)}{((2-\delta)(2+\delta(n-1)))^2} \text{ and } \sigma_I = \psi - \left(\frac{2(2-\delta+\delta(1-\beta)(n-1))}{(2-\delta)(2+\delta(n-1))}\right)^2$$

and

$$\sigma_C = \frac{2(2-\delta+\delta(1-\beta)(n-1))}{((2-\delta)(2+\delta(n-1)))^2}(2\beta - \delta)$$

Notice that the nature of interaction in R&D is determined by the interplay between knowledge spillovers and product rivalry: if $2\beta > \delta$ then $\sigma_C > 0$; hence when knowledge spillovers dominate product rivalry, R&D complementarity is pervasive in the industry. If $2\beta < \delta$ then $\sigma_C < 0$; hence when product rivalry dominates knowledge spillovers, R&D substitutablity is pervasive in the industry. Finally, if $2\beta = \delta$ then $\sigma_C = 0$; hence when knowledge spillovers and product rivalry are balanced, no interaction occurs between firms in R&D.

Figure 1: Interaction in R&D



Applying the results of the previous section, the CbC funding problem is

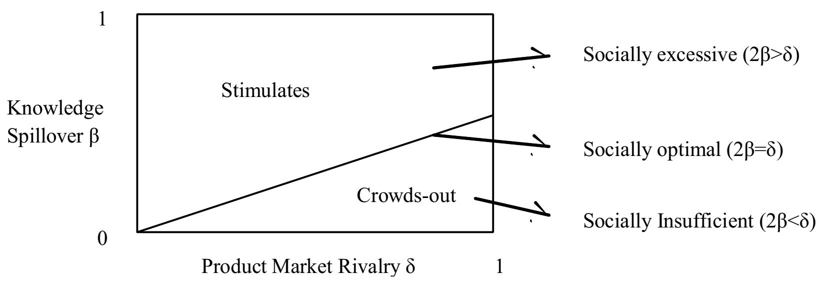
[21] Suppose social welfare is the sum of consumer surplus, industry profits and an external social benefit deriving from R&D spillovers to firms and consumers in other industries, $W = (\sum \frac{q_i^2}{2} + \frac{\delta}{2}\sum_{i \neq j}^{n} q_i q_j) + \sum \pi_i + B(\sum x_i)$, in which $B > 0$. The social optimum is in the spirit of the second best since the production behaviour of firms is taken as given.

[22] See the Appendix for these derivations.

$$s^{CbC} - s^* = (n-1)\sigma_C \Delta$$

If knowledge spillovers dominate product rivalry then R&D subsidies stimulate privately-financed R&D and government over-funds research under the CbC rule. If product rivalry dominates knowledge spillovers then R&D subsidies crowd-out privately-financed R&D and government under-funds research under the CbC rule. Finally, if knowledge spillovers and product rivalry are balanced then CbC funding is socially optimal.

Figure 2: R&D Subsidy Effects and the Performance of CbC Funding



Notice that a close relationship exists between the direction of the CbC funding problem and an industry's position in knowledge spillover-product rivalry space.

What is the effect of an inelastic supply of R&D inputs on the direction of the CbC funding problem? Suppose that the effective R&D cost is given by

$$y_i(x_1, .., x_n, s_i) = -s_i x_i + \phi(\textstyle\sum_{j \neq i} x_j) x_i + \frac{1}{2}\psi x_i^2.$$

Interaction in R&D costs is captured by the parameter $\phi > 0$. This parameter measures the extent to which R&D undertaken by rival firms increases the R&D cost of fim i. Solving the model as before, the first order condition of the firm's R&D decision is given by

$$\frac{\partial \pi_i}{\partial x_i} = \alpha + s_i - \sigma_I x_i + \textstyle\sum_{j \neq i} (\sigma_C - \phi) x_j$$

Hence, the CbC funding problem is

$$s^{CbC} - s^* = (n-1)(\sigma_C - \phi)\Delta$$

Observe that if knowledge spillovers dominate product rivalry then limited R&D resources can remove a CbC over-funding problem. On the other hand, if product rivalry and knowledge spillovers are balanced then limited R&D inputs can create a CbC under-funding problem. The following propositions summarize the main findings associated with CbC funding in the presence of endogenous interaction in R&D:

Proposition 4 *Over-funding occurs in industries characterized by high knowledge spillovers, weak product market rivalry and an elastic supply of R&D inputs.*

Proposition 5 *Under-funding occurs in industries characterized by weak knowledge spillovers, intense product market rivalry and an inelastic supply of R&D inputs.*

It should be noted the CbC rule performs well in many distinct settings. Consider the following examples in which CbC funding is socially optimal: First, if $2\beta = \delta$ and $\phi = 0$ then $s^{CbC} = s^{*}$; hence when knowledge spillovers and product market rivalry are balanced and there is no interaction in R&D costs. Second, if $2\beta > \delta$ and $\phi > 0$ with $\sigma_C = \phi$ then $s^{CbC} = s^{*}$; hence when knowledge spillovers are high, product rivalry weak and R&D inputs are sufficiently limited. Third, if $\delta > 2\beta$ and $\phi < 0$ with $\sigma_C = \phi$ then $s^{CbC} = s^{*}$; hence when product rivalry is intense, knowledge spillovers weak and positive synergies exist between firms in R&D costs.

4 Conclusions

The main policy conclusion is that under the CbC rule, government over-funds research in industries in which innovations tend to be complementary and under-funds research in industries in which innovations tend to be substitutative. In addition, the paper reveals a close relationship between the direction of this funding problem and an industry's knowledge spillover and product market rivalry chararacterisitics.[23]

There is significant evidence interaction in R&D differs greatly from one industry to the next (Jaffe, 1986; Levin, 1988; Bernstein, 1988).[24] Bloom et al. (2007) provide strong evidence that knowledge spillover-product market rivalry characteristics vary widely across industries.[25] Combined with the main conclusion these observations are suggestive, governments may be over-funding research in some industries at the expense of research in other under-funded industries with the implication that reallocating some of this funding could significantly improve the effectiveness of public support to business R&D.[26]

[23] In a recent paper, Bloom et al. (2007) develop a methodology to identify the seperate effects of knowledge spillovers and product market rivalry on private inventive activity based on technological and product market closeness measures similar to Jaffe (1986).

[24] According to Levin (1988), innovations in industries such as aircraft, semi-conductors, computers, electronics components and communicatons equipment tend to be complementary. While, innovations in industries such as chemicals and pharmaceuticals tend to be substitutative.

[25] See their findings on the pharmaceutical, computer hardware and telecommunications industries.

[26] Note that the distribution of government R&D budget outlays across industries is often highly skewed (OECD, 2007).

This paper does not recommend policy makers should discard the CbC rule. On the contrary, the analysis finds the rule performs well in several distinct settings. However, agencies must be careful in applying the rule. The rule may need to be adjusted in the presence of interaction in R&D. An agency should seek to identify possible indirect funding effects.[27] In particular, it should reduce the CbC subsidy in the presence of pervasive R&D complementarity and increase the CbC subsidy in the presence of pervasive R&D substitutablity.

In relation to other policy instruments, patent systems and competition policies are currently in use in many countries. These policy instruments, by altering industry knowledge spillover-product rivalry characterisitics, may have a positive or negative effect on the efficiency of CbC funding. For example, if competition policy succeeds in increasing the intensity of product market competition in an industry then it may remove a CbC over-funding problem if knowledge spillovers are high or create a CbC under-funding problem if knowledge spillovers are weak.

In relation to future research, the paper should be seen as a first step in examining whether governments over-fund or under-fund research in specific industries. The paper makes some restrictive assumptions which need to be relaxed in more complex situations. Examples of such situations include: heterogeneity in R&D interaction across firms, several intervening and uncoordinated governments, biased government preferences.

For example, several markets have become global in recent decades with governments eager to support the research of their national champions, e.g Airbus and Boeing. In such situations, governments may be more concerned with improving the market value of domestic champions and less concerned with closing the spillover gap associated with their firm's R&D projects. The interplay of national interests and international interaction in R&D may have positive implications for the performance of publicly funded R&D. For example, under international cooperation, CbC funding would be socially excessive in the presence of trans-national R&D complementarities. The uncoordinated persuit of national interest may restrict this over-funding.

There is nothing in the model of section two which formally restricts its interpretation to R&D. This model captures a situation in which peer effects (homogenous across members) shape aggregate group behaviour with consequences for broader society and a benevolent authority influences private incentives in a case-by-case manner. The model should have a wide number of applications and extensions in other policy relevant areas, e.g. crime, terrorism, social movements, integration of immigrant groups, property bubbles.

[27] The use of historical data should be restricted to industries in which these characterisitics remain relatively stable over time. Market structure, and possibly knowledge spillover patterns, evolve with innovation. Using historical data to predict future knowledge spillover-product rivalry characteristics would be highly erroneous in industries in which these characteristics change rapidly with technological change.

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Appendix

Equilibrium R&D given subsidy policy: The best response function of each firm is $b_i((x_j)_{j\neq i}, s_i) = \frac{1}{\sigma_I}\alpha + \frac{1}{\sigma_I}s_i + \sum_{j\neq i}\frac{\sigma_C}{\sigma_I}x_j$. Solving this linear system of equations gives the Nash equiblrium R&D $x_i^*(s_1,..,s_n) = \widehat{x}_i +$

$\frac{\sigma_I(\sigma_I-(n-2)\sigma_C}{A}s_i + \sum_{j\neq i}\frac{\sigma_C}{A}s_j$, in which $A = (\sigma_I + \sigma_C)(\sigma_I - (n-1)\sigma_C) > 0$. The term $T_i := \frac{\sigma_I(\sigma_I-(n-2)\sigma_C}{A}$ denotes the total effect of a subsidy on the recipient firm's R&D. From the decomposition, this total effect consists of a direct effect, D_i and $(n-1)$ indirect feedback effects, F_{ij}, that is $T_i = D_i + \sum_{j\neq i} F_{ij}$. From the firm's best response function $D_i = \frac{1}{\sigma_I}$. Substituting in the direct effect and the total effect and solving reveals the feedback effect is given by $\sum_{j\neq i} F_{ij} = T_i - D_i = \sum_{j\neq i}\frac{\sigma_C^2}{\sigma_I A}$. Hence, equilibrium R&D given subsidies can be rewritten as

$$x_i^*(s_1,..,s_n) = \widehat{x}_i + \sum_{j\neq i} F_{ij}s_i + \sum_{j\neq i} C_{ij}s_j + D_i s_i$$

in which $F_{ij} = \frac{\sigma_C^2}{\sigma_I A}$, $C_{ij} = \frac{\sigma_C}{A}$ and $D_i = \frac{1}{\sigma_I}$ are respectively the feedback, direct and cross effect of subsidy on R&D.

Optimal subsidy: Optimal policy requires that govenment equates $x^{**} = x^*(s)$. The policy equilibrium is $x^*(s) = \widehat{x} + (n-1)(F+C)s + Ds$. Hence, $x^{**} = \widehat{x} + (n-1)(F+C)s + Ds$. Rearranging and using the fact that the investment gap $\Delta = x^{**} - \widehat{x}$ leads to the equation $\Delta = (D + (n-1)(F+C))s$. Substituting in for $D = \frac{1}{\sigma_I}$, $F = \frac{(n-1)\sigma_C^2}{\sigma_I A}$, $C = \frac{\sigma_C}{A}$ and $A = (\sigma_I + \sigma_C)(\sigma_I - (n-1)\sigma_C)$ gives $\Delta = \frac{1}{(\sigma_I-(n-1)\sigma_C)\Delta}s$. Hence, the optimal subsidy is $s^* = \sigma_I\Delta - (n-1)\sigma_C\Delta$.

Investment gap: Social welfare is $W = \sum \pi_i(x_1,..,x_n) + B(\sum x_i)$. The planner equates $\alpha - \sigma_I x_i + 2\sum_{j\neq i}\sigma_C x_j + B = 0$, for all $i = 1,..,n$. The restriction $\sigma_I > 2(n-1)\sigma_C$ ensures the existence of a unique interior social optimum. Invoking symmetry and rearranging gives socially optimal R&D $x^{**} = \frac{B+\alpha}{\sigma_I-2(n-1)\sigma_C}$. In the laissez faire scenario, each firm equates $\alpha - \sigma_I x_i + \sum_{j\neq i}\sigma_C x_j = 0$. Invoking symmetry, the laissez faire R&D is $\widehat{x} = \frac{\alpha}{\sigma_I-(n-1)\sigma_C}$. Then, taking the difference and rearranging, the investment gap is $\Delta = \frac{B}{(\sigma_I-2(n-1)\sigma_C)} + \frac{(n-1)\sigma_C}{(\sigma_I-(n-1)\sigma_C)(\sigma_I-2(n-1)\sigma_C)}\alpha$. Notice that if $\sigma_C < 0$ then $\Delta > 0$ provided $B > -\frac{(n-1)\sigma_C}{(\sigma_I-(n-1)\sigma_C)}$.

Comparative Static properties of the CbC funding problem:
External social benefits: note that $\frac{\partial(s^{CbC}-s^*)}{\partial B} = (n-1)\sigma_C\frac{\partial\Delta}{\partial B}$ and $\frac{\partial\Delta}{\partial B} = \frac{B}{(\sigma_I-2(n-1)\sigma_C)} > 0$, hence $\frac{\partial(s^{CbC}-s^*)}{\partial B} > 0$.

Effect of R&D interaction on the investment gap: note that
$\frac{\partial\Delta}{\partial\sigma_C} = \frac{2(n-1)B}{(\sigma_I-2(n-1)\sigma_C)^2} + \frac{(n-1)(\sigma_I^2-2(n-1)^2\sigma_C^2)}{[(\sigma_I-(n-1)\sigma_C)(\sigma_I-2(n-1)\sigma_C))]^2}\alpha > 0$.

Effect of intensity of R&D interaction on the magnitude of the CbC funding problem: the product rule of differentiation implies that $\frac{\partial(s^{CbC}-s^*)}{\partial\sigma_C} = (n-1)(\sigma_C\frac{\partial\Delta}{\partial\sigma_C} + \Delta)$. Note that $\frac{\partial\Delta}{\partial\sigma_C} > 0$ and by assumption $\Delta > 0$. Hence, if $\sigma_C > 0$ then $\frac{\partial(s^{CbC}-s^*)}{\partial\sigma_C} > 0$. On the other hand, if $\sigma_C < 0$ then $\frac{\partial(s^{CbC}-s^*)}{\partial\sigma_C} > 0$

if and only if $\Delta > -\sigma_C \frac{\partial \Delta}{\partial \sigma_C}$. Explicitly, note that $\frac{\partial(s^{CbC}-s^*)}{\partial \sigma_C} = \frac{(n-1)B\sigma_I}{(\sigma_I-2(n-1)\sigma_C)^2} + \frac{(n-1)\sigma_C\sigma_I(2\sigma_I-3(n-1)\sigma_C)}{[(\sigma_I-(n-1)\sigma_C)(\sigma_I-2(n-1)\sigma_C))]^2}\alpha$ implies that $\frac{\partial(s^{CbC}-s^*)}{\partial \sigma_C} > 0$ provided that $B > -\frac{(n-1)\sigma_C\sigma_I(2-3(n-1)\sigma_C)}{(\sigma_I-(n-1)\sigma_C)^2}$. A negative relationship, $\frac{\partial(s^{CbC}-s^*)}{\partial \sigma_C} < 0$, occurs when B satisfies $-\frac{(n-1)\sigma_C}{(\sigma_I-(n-1)\sigma_C)} < B < -\frac{(n-1)\sigma_C\sigma_I(2-3(n-1)\sigma_C)}{(\sigma_I-(n-1)\sigma_C)^2}$.

Derivation of the reduced-form R&D payoff functions: Firm profits are $\pi_i = p_i(q_i, q_j)q_i - c(x_i, x_j) - y(s_i, x_i)$. Standard derivations give the Nash Cournot outputs, $q_i(c_1, ..c_n) = \frac{(2-\delta)a-(2+\delta(n-2))c_i+\sum_{j\neq i}\delta c_j}{(2-\delta)(2+\delta(n-1))}$. Notice that if $\delta = 0$ then firms produce the monopoly level of ouput $q_i = \frac{a-c_i}{2}$. If $\delta = 1$ then firms produce well known the homogenous product cournot level of output $q_i = \frac{a-c_i+\sum_{j\neq i} c_j}{n-1}$. Substituting in the cost formulation and rearranging terms gives $q_i(x_1, .., x_n) = \frac{(2-\delta)(a-c)+(2-\delta+\delta(1-\beta)(n-1))x_i+\sum_{j\neq i}(2\beta-\delta)x_j}{(2-\delta)(2+\delta(n-1))}$. Substituting these outputs into the profit function yields the R&D payoff function of the firm, $\pi_i(x_i, x_j, s_i) = [\frac{(2-\delta)(a-c)+(2-\delta+\delta(1-\beta)(n-1))x_i+\sum_{j\neq i}(2\beta-\delta)x_j}{(2-\delta)(2+\delta(n-1))}]^2 + s_i x_i - \frac{1}{2}\psi x_i^2$. Taking the first order condition

$$\frac{\partial \pi_i}{\partial x_i} = \frac{2(2-\delta)(2-\delta+\delta(1-\beta)(n-1))}{((2-\delta)(2+\delta(n-1)))^2}(a-c) + s_i - [\psi - 2(\frac{(2-\delta+\delta(1-\beta)(n-1))}{(2-\delta)(2+\delta(n-1))})^2]x_i + \sum_{j\neq i} \frac{2(2-\delta+\delta(1-\beta)(n-1))}{((2-\delta)(2+\delta(n-1)))^2}(2\beta-\delta)x_j = 0$$

which is of the form

$$\frac{\partial \pi_i}{\partial x_i} = \alpha + s_i - \sigma_I x_i + \sum_{j\neq i}\sigma_C x_j = 0$$

Notice that, knowledge spillovers discourage R&D investment provided the intensity of market rivalry is not too large: if $\delta = 0$ then $\frac{\partial}{\partial \beta}(\frac{\partial \pi_i}{\partial x_i}) > 0$ and if $\delta = 1$ then $\frac{\partial}{\partial \beta}(\frac{\partial \pi_i}{\partial x_i}) < 0$.