# Endogeneizing know-how flows through the nature of R&D investments

*by*

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**Abstract**
In this paper we carefully link knowledge flows to and from a firm's innovation process with this firm's investment decisions. We present a model of a leading technological firm facing a competitive fringe. The leading firm considers three types of investments: investments in applied research, investments in basic research, and investments in intellectual property protection. Our model assumes that the firm can effectively access incoming knowledge flows by doing basic research. These incoming spillovers serve to increase the efficiency of own applied research. The firm can at the same time influence outgoing knowledge flows, improving appropriability of its innovations, by investing in protection. Our results indicate that the leading firm with a small budget for innovation will not invest in basic research. This occurs in the short run, when the budget for know-how creation is restricted, or in the long-run, when market opportunities are low, when legal protection is not very important, or, when the pool of accessible and relevant external know-how is limited. The ratio of basic to applied research is non-decreasing in the size of the pool of accessible external know-how, the size and opportunity of the market, and, the effectiveness of intellectual property rights protection. This indicates the existence of economies of scale in basic research due to external market related factors.

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## *1. Introduction*

The appropriation of the benefits to innovation is unlikely to be perfect because the results of innovations spill over to other firms imposing a positive externality on these firms. This public good nature of know-how has profound implications for a firm's innovative activities and for government policies. A large body of theoretical models has developed around the impact of spillovers on firms' incentives to invest in R&D under different investment regimes (see De Bondt (1996) for a review). Empirical studies trying to assess the importance of spillovers have grown accordingly (see Griliches (1992) and Geroski (1996) for a review). Furthermore, public policy makers have recognized the public good character of (technological) know-how and have shifted attention from stimulating R&D expenditures directly to strengthening the diffusion potential of innovation systems.

There are two important features of spillovers that the theoretical models have failed to take into account. First, spillovers as inputs should be distinguished from spillovers as outputs when analyzing appropriation problems. On the one hand, technological spillovers are an input for the innovation process of an innovating firm. Combining this external knowledge with internal knowledge results in innovations—new, higher quality products and processes. On the other hand, innovating firms worry about the applied knowledge that these innovations produce and which spills over to rival firms. Therefore, these innovators try to maximize the benefits from the external knowledge they can access from the environment—the incoming spillovers, and minimize the negative effects from the spillovers generated for imitators—the outgoing spillovers. In almost all theoretical I.O. models, firms generate and receive spillovers to the same extent. But although firms may at the same time benefit from the stock of available external know-how while having their own know-how becoming part of the public domain, these effects are not necessarily symmetric. Martin (1999) similarly distinguishes in a two-firm R&D patent race between input spillovers and post-innovation imperfect appropriability, where he measures appropriability through the size of the license fee that the winner of the innovation race can charge the loser in a compulsory licensing contract. He finds that the value of the firm is typically maximized when there are high incoming spillovers and when appropriability is high.

Second, spillovers are not exogenous. Firms have to make costly investments in order to affect the usefulness of these incoming spillovers or limit the usefulness of outgoing spillovers to rival firms. Hence, firms, through their investment decisions, effectively endogenize knowledge flows between organizations. So far spillovers have mostly been treated exogenously as involuntary flows, which cannot be affected by the firms. In this view, spillovers are determined by the nature of the technology or by market forces. In addition, they are assumed to be industry-specific rather than firm-specific, and, hence, identical for all firms (see d'Aspremont and Jacquemin (1988), De Bondt and Veugelers (1991), De Bondt (1996) and the references therein). Recently, some I.O. models have taken into account that firms can indeed manage these spillovers through organizational decisions. Nevertheless, no costly investments are necessary in order to benefit from these spillovers. For in the Research Joint Venture scenario of Kamien et al. (1992) cooperating partners can voluntarily increase the spillovers among them (see also Katsoulacos & Ulph (1998)). Cohen and Levinthal (1989) pioneered the idea that firms can try to increase incoming spillovers by investing in "absorptive capacity", i.e. spillovers are more efficient in reducing own costs when the firm is engaged in own R&D. This notion of absorptive capacity has been integrated in the I.O. models on R&D cooperation by Kamien & Zang (2000). They show that when R&D directions of partners are sufficiently dissimilar, larger spillovers might induce non-cooperative R&D levels to be larger than cooperative R&D levels due to investments in absorptive capacity. But not only will firms have to invest to be able to absorb, firms wanting to protect themselves from appropriation of their innovations by other firms also have to develop explicit (costly) activities designed to manage outgoing spillovers. This is an ignored issue in the theoretical literature, which seems to rely exclusively on legal mechanisms to protect innovations. Teece (1987) already pointed to the value of co-specialized assets for the appropriation of innovation results. Furthermore, empirical evidence suggests that complementarity between the legal and strategic protection is quite important.

In this paper we carefully model the interactions between knowledge flows on the one hand and the firm's innovative decisions on the other hand. In doing so, we endogeneize both in- and outgoing knowledge flows, taking into account that firms will attempt to affect the impact of knowledge flows to and from the firm through their decisions on the size and nature of R&D activities undertaken. In our model we distinguish between three possible activities: investments in applied research, investments in absorption through basic research, and investments in intellectual property protection. We view basic research as an important avenue through which absorptive capacity can be build. Own R&D investment of the basic kind allows the firm to learn more from the information that is freely available, i.e. this investment serves to develop the absorptive capacity of the firm. At the same time a firm that is more sophisticated in its own R&D process is able to improve its appropriability through the added complexity of the resulting processes and products. Hence, while investments in intellectual property protection avoid outgoing knowledge flows, investments in absorptive capacity through basic research generate incoming knowledge flows. One possible set-up for our basic and protective investments could come through the labour market for R&D personnel (see Schmutzler & Gersbach (2000), and also Fosfuri et al. (1998)). The offers firms make to attract R&D personnel from outside and the offers made to keep own R&D personnel inhouse, can be seen as payments to optimize respectively incoming and outgoing spillovers.

The model focuses on three critical exogenous variables to derive predictions about the relation between know-how flows and technology investments. These variables are the pool of external know-how that the firm can access, the opportunities provided by the market through its size and the willingness to pay for quality, and, the effectiveness of intellectual property rights protection through legal means. Increases in any of these variables will increase the technology investments by the firm, both in creative and protective investments. Our results indicate that firms need to spend on applied research in order to keep a quality edge over their fringe rivals. At the same time, they need to spend on protection to prevent diffusion of their innovations to these fringe firms. More interestingly, we find that firms with small budgets for innovation will not invest in basic research. This occurs in the short run, when the budget for know-how creation is restricted, or in the long-run, when the market size is too small, when legal protection is not very important, or, when the pool of accessible and relevant external know-how is restricted.

Once firms start accessing external know-how by spending on basic research as a way to create effective know-how, the allocation of technology expenditures between basic and applied research will increasingly favor basic over applied as larger budgets become available. This might happen because of a larger pool of accessible external know-how that, overall, will lead to more spending on technology, both in creating internal know-how and in protecting this newly created own know-how base.

The external know-how level not only increases internal basic research which is needed to access this pool of know-how, but it will also make applied research more productive and hence boost spending on the latter as well. Similar effects on spending are present in larger markets, markets with a higher willingness to pay for quality, and, in markets where intellectual property rights protection is tighter. Therefore, our model not only predicts when technology investments increase as a function of market factors, thereby explaining the complementarity between internal and external sourcing. But it also explains the increasing returns to basic research as a consequence of these external factors, rather than because of the minimum efficient scale of a research department. The model further incorporates complementarity between strategic and legal protection: when intellectual property right protection is tighter the firms will have a larger incentive to invest not only in creation of know-how but also in protection of this newly created know-how.

Section 2 develops a simple analytical model that allows us to distinguish between incoming and outgoing spillovers in order to study the relationship between both types of spillovers and the firm's innovative activities. When setting out the model, we will use empirical evidence to corroborate some of the assumptions made.[1] We are able to derive analytical results on the allocation of investments in protective activities as well as investments in applied and basic research to optimize effective know-how building by combining internal and external know-how. These results are presented in Section 3. A final section concludes.

## *2. Model set up*

A simple model is used to highlight the nature of the incentives of firms to invest in technology and how firms allocate these investments over different activities such as applied research, basic research to absorb external know-how, and protection.

[1] The main source of information is a survey on innovation in the Belgian manufacturing industry. The data were collected as part of the Community Innovation Survey conducted by Eurostat in the different EU-member countries in 1993. A representative sample of 1335 Belgian manufacturing firms was selected resulting in 737 usable questionnaires. About 60% of the firms in the sample claim to innovate, while only 40% do not innovate. We restrict the analysis to the innovative firms in the sample. These firms introduced new or improved products or processes in the last two years and returned a positive amount spent on innovation. Due to missing data, we end up with 445 firms in this innovation sample. For these firms, qualitative information is available on the nature of their innovative activities. Unfortunately, the data do not provide quantitative data on technology expenditures in each category, i.e. on applied and basic research, and on investments made on protection.

### 2.1. Market structure

In the output market, consumers decide whether to buy a unit of the product. A consumer who buys a unit of product of quality $s$ at a price $p$ obtains a utility of:

$$U = \theta s - p,$$

where the parameter $\theta$ is a measure of taste for quality. A consumer who does not buy obtains a utility normalized to zero. The parameter $\theta$ is uniformly distributed among customers between $[\theta_l, \theta_h]$ with $\theta_h - \theta_l = 1$ and $\theta_l \leq 1$.

The market structure is one where a leading firm ($L$) is facing a fringe of followers, producing a product differentiated in quality: while the leading firm $L$ produces a good of quality $s_L$, the firms in the fringe each produce a good of quality $s_F$ lower than $s_L$. Only the leading firm is considered to be innovation active. The followers are imitators with respect to the innovations introduced by the leading firm. The unit cost of production is $c$ for all firms, with $c \leq \theta_l s_F$. While this market leader structure allows to keep the model tractable, it is not general and for instance cannot be applied to markets with a small number of equally sized firms such as in car manufacturing or pharmaceuticals (see section 3.4 for a discussion on extending the competition framework to include innovating rivals). Nevertheless, a large number of innovative firms seem to perceive their own position as leading, at least in the segments of the markets in which they are active.[2]

The firms in the fringe behave competitively, each producing a product of equal quality $s_L$, and therefore pricing at marginal cost:

$$p_F = c.$$

A consumer with taste parameter $\theta^*$ is indifferent between buying from the leader at the price $p_L$ or from a follower at the price $p_F = c$ if and only if

$$\theta^* = (p_L - c)/\Delta s \quad with \quad \Delta s = s_L - s_F.$$

The consumers with a taste characteristic higher than that of the indifferent consumer will buy from the leader, while the others will choose the product of the fringe firms. Therefore, the demand for the leading product is:[3]

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[2] In a Belgian innovation survey, 82% of all 602 innovation-active respondents characterized their competitive position as leaders or at least among the leading companies (Source: IWT (1999)).

[3] The following expression for $D_L(p_L)$ is only valid if $p_L - c \geq \theta_l \Delta s$; otherwise, $D_L(p_L) = (\theta_h - \theta_l)M = M$.

$$D_L\,(p_L) = \left[q_h - \frac{p_L - c}{\Delta s}\right] M\,,$$

with $M$ a parameter for the size of the market.

The leader firm $L$ chooses the price $p_L$ to solve:

$$\underset{p_L}{Max}\;\; (p_L - c)\, D_L(p_L).$$

This results in the following expression for the firm's profit function:

$$P_L = N\, Ds,$$

with $N \equiv M\ q_h{}^2/4$. That is, $N$ is a measure of both the size of the market and the consumers' willingness to pay for high-quality products. Note that $P_F = 0$, since we have a competitive fringe. For notational simplicity, we will denote $P = P_L$.

The leader's profit function implies that the difference in quality levels between the leader and the follower is crucial in determining his profitability. The quality level of the product is determined by the R&D technology in a simple relationship:

$$s_I = X_I,$$

with $X_I$ the leading firm's effective know-how base. Innovative activities that expand the knowledge base of the leading firm directly improve the quality of the product.[4] The previous expression implies that the difference in effective know-how base, $\Delta X = \Delta s$, becomes a crucial variable for the leader's profitability.

## 2.2. Technology Investment

The fringe firms all produce the same product and have zero profits. Hence, incentives to innovate are absent. Therefore, we can ignore any investments on their part to build up their effective knowledge base $X_F$. This allows to concentrate on the leading firm, who, while competing with the fringe firms, has to decide not only on the size of its investment budget, but also on the allocation of this budget to three different generic types of Technology Investment:

*A*: Budget allocated to Applied R&D,

[4] Product improvement is a major motive for firms to engage in innovative activities, being most typically of the incremental product R&D type. In EUROSTAT/CIS survey results for Belgium, innovation-active firms ranked improving product quality as the most important objective. This

(Griliches (1998)).

The pool of external know-how is located outside the firm's industry and hence, being not immediately applicable, requires absorptive capacity. Survey studies characterizing spillovers find that *independent R&D* is one of the most efficient channels for absorbing external knowledge (see, for instance, Levin et al (1987), Mansfield (1985), and Harabi (1995)). As in the absorptive capacity model of Cohen & Levintahl (1989), firms need to conduct R&D to be able to assimilate spillovers. Diving further in what constitutes "absorptive capacity", Rosenberg (1990) stresses the importance attached to performing *basic research* by companies that see it "as a ticket of admission to an information network":

> "A basic research capability is often indispensable in order to monitor and evaluate research being conducted elsewhere"

Rosenberg suggests that the effective spillover level is an endogenous variable, depending on the basic research capability of an organization. However, a sharp distinction between basic and applied research is very difficult to draw, given the high degree of interaction. Firms often need to do basic research in order to understand better how to conduct research of a more applied nature. Quoting Rosenberg (1990) again :

> "A basic research capability is essential for evaluating the outcome of much applied research for perceiving its possible implications…"

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product enhancement is nevertheless typically in line with cost reduction, leaving product and process R&D often combined (Miravete and Pernías, 2000).

Therefore, we will view *basic research* in its capacity to enable the absorption of external information. Without basic research externally available know-how cannot become part of the effective knowledge base of a company. Lim (2000) argues that investments in absorptive capacity can take two particular forms. Firms can invest in own R&D, which he considers pure basic research, or, firms can invest in connectedness with sources of external information. Our definition of basic research captures both of these types of investments. Section 3.4 discusses the case where we allow for pure basic research in addition to investments for accessing external knowledge. Furthermore, one of the extensions related to R&D cooperation explicitly takes Lim's connectedness view of these investments. Accepting this definition of basic research implies that it is complementary to own applied R&D and external information becomes a complement to internal development.[5] Basic R&D therefore increases the efficiency of applied research. In this model *applied R&D* is defined to be specific to the firm's business and, hence, necessary to develop an effective knowledge base that serves to improve the firm's position. The effective knowledge base of a company $X_L$ is thus modeled as follows:

$$X_L = A^a \, [1 + b(B)\, K]^b$$

The parameters $a$ and $b$, where $a+b < 1$, are a measure of the efficiency of resp. applied and basic R&D technology. The total stock of outside know-how, $K$, and the firm's incoming spillovers, i.e. the rate of access of a firm to $K$, $b(B)$, influence the effective knowledge base of the leading company. While $K$ captures the quantity or amount of knowledge generated by others, $b(B)$ indicates the fraction of knowledge that is captured by the firm. The effective absorption of the external know-how occurs through the basic research effort of the firm as indicated by the dependence of the spillover on basic R&D. For tractability we will assume a linear relation:[6] $b(B) = b.B$ resulting in

[5] The CIS/EUROSTAT data supports the complementarity between internal and external sourcing. Of the 348 firms (or 78% of the sample innovative firms) who rate vertical links at least moderately important (i.e. a score of 3, 4 or 5 on a scale of 1 to 5), 264 (or 76%) simultaneously rate internal information to be of high to crucial importance (i.e. a score of 4 or 5). Similarly, for the firms who rate publicly available information at least moderately important (N=229), the percentage of them rating internal information important to crucial is 77%. For firms rating research institutes as at least a moderately important source of information (N=102), the percentage rating internal information very important to crucial is 81%. To compare, for the total sample of innovative firms (N=445), 70% rate internal sources of high or crucial importance. All the reported numbers show a significant difference. The various Chisq-tests are significant at the 1% level.

[6] We relax this assumption when discussing the extension in section 3.4.

$$X_L = A^a \, [1 + b \, B \, K]^b,$$

Note that in our model, basic research, by definition, only serves to absorb external know-how. When $K$=0, there is no value to investing in $B$. (see section 3.4 for alternative specifications).

One would expect that the amount and nature of relevant external know-how, $bK$ depends on firm-specific as well as industry-specific elements. Henderson & Cockburn (1996) show that the organization of the firm and its strategy might allow it to take more advantage of spillovers. Furthermore, Pavitt's (1984) classification of industries into science-based sectors, supplier dominated sectors or sectors supplying specialized inputs to other sectors indicates the importance of different types of sources of external know-how for different industries.

Note that the pool of external know-how is not directly affected by a competitor's know-how. Competitors, the fringe firms in the model, only imitate but do not innovate and hence do not create new knowledge, adding to K. In section 3.4 we relax this assumption. Nevertheless, the absence of competitors' know-how in the pool of external information is in line with empirical observations that competitors are of less importance as source of information for innovation, especially as compared to vertically related companies.[7]

The effective knowledge base of a company cannot be kept fully proprietary. Once developed it will become part of the public domain. These outgoing spillovers will directly affect the leading firm's competitive position to the extent that they can be accessed by its competitors, i.e. the competitive fringe.[8] While the pool of publicly available know-how requires basic research in order to be effectively translated into quality improvements, and, therefore, is not accessible to the fringe firms, the effective know-how base of the leader is already sufficiently product specific that it can be absorbed by the fringe firms without any own innovative activities.

[7] When asked to rank various sources of external information according to their importance for the innovation process on a scale from 1(=not relevant) to 5(=crucial), 31% of the innovating firms in the Belgian CIS/EUROSTAT survey rated competitors as not relevant or of only minor relevance (=score of 1 or 2), while only 8.5% rated them as crucial. This is in sharp contrast to vertical sources of information (clients and/or suppliers), which were rated as not relevant or of only minor relevance by only 5% of the innovative firms, and as crucial sources of information by 16%. The (lack of) importance of competitors shows little significant differences across sectors. Only in machinery, competitors seem to be rated as more important as compared to other sectors.

[8] See Amir & Wooders (1998) for a model with endogenous innovator-imitator roles where spillovers flow from the high R&D intensive firm to the low R&D intensive firm. In our model, we assume the leader-follower relation exogenously.

Absorptive capacity through basic research is hence only considered for accessing external know-how that is not yet product specific. The process of competitive diffusion is characterized as follows:

$$X_F = a\, X_L,$$

where $a$ measures the process of diffusion (ease of imitation) to rivals. This process of diffusion is partly exogenous, affected by the effectiveness of legal protection or the appropriability degree of the technology. But the firm can also influence the ease of imitation by investing in protection. This type of technology investments should be distinguished from applied or basic R&D expenditures which are inputs into the innovation process. The firm can make strategic investments to increase the complexity of the product or process design or to improve secrecy. Or, when tacit knowledge is embodied in human capital, protective investments may take the form of attractive wage packages to keep key R&D personnel (see Schmutzler & Gersbach (2000)). Even if an intellectual property protection system is available, the firm typically has to make investments to take advantage of the possibilities provided by the legal protection system. Patent rights are typically not self-enforcing and require costly expenditures by patent-holders to exercise their rights. This interaction between legal and strategic protection to influence the diffusion process is formalized as follows:

$$a(P) = 1 - [(R + 1)\, P^{p}]$$

with $p < 1 - (a + b)$. The loss of appropriation depends on the level of investment in protection, $P$, and level of legal rights protection, $R$. The efficiency of the strategic protection technology is represented by $p$.[9] Both $R$ and $p$ are assumed to be exogenous to the firm's investment decision.

This formalization allows capturing the importance of strategic protection. Without protective investments $P$, $a = 1$. In addition, legal protection mechanisms cannot substitute for these protective investments: $R$ serves as a complement to strategic protection. Firms need some investment $P$ in order for them to be able to benefit from any legal protection mechanism. Often patents provide little protection

[9] The parameter $p$ only measures the efficiency of strategic protection Note that the model can easily be transposed into $a(P) = 1 - [P\,(R + 1)]^{p}$ with $p$ measuring the overall strength of the appropriation regime, replacing in the further discussion $(R + 1)$ by $(R + 1)^{p}$.

because the legal requirements for upholding their validity or for proving their infringement are high (Teece, 1987).[10]

The data from the CIS-survey confirm the importance of strategic investments as the most important protective mechanism: 389 out of the 445 innovative firms (or 87.5%) rate strategic protection through secrecy, complexity or lead time at least as important as patent protection. There are 140 innovative firms (or 31.5%) that rate legal protection as not relevant (i.e. a score of 1), while the average score for legal protection is 1.9. In sharp contrast, only 14 innovative firms in the sample (or 3%) rate strategic protection mechanisms of no relevance and the mean score for strategic protection is 3.3. Of these 14 firms, 13 (or 93%) simultaneously rate legal protection to be not relevant. Hence, the few firms that do not invest in strategic protection, seem to be ignoring strategic protection for other reasons than the possibility of substituting it with legal protection. The complementarity between strategic and legal protection can be further documented. Of the 84 innovative sample firms who rate legal protection at least moderately important (i.e. 19% of the total sample), 75 firms (or 89%) also rate strategic protection at least moderately important.[11]

Due to diffusion, the firm can only keep part of its know-how proprietary. The ratio of protected know-how to actual know-how, i.e. $(1 - a)$, can be influenced by the firm through its investments $P$. The stock of protected know-how $(1 - a)X$, is in our model equal to the difference in quality $\Delta s$ :

$$\Delta s = (1 - a(P))\, X = [(R + 1)\, P^{p}]\, X.$$

If the firm fails to invest in strategic protection, i.e. $P = 0$, the diffusion of know-how to fringe competitors will eventually wipe out the profitability of the leading firm. In our model this implies that $\Delta s = 0$ and hence $P = 0$.

In summary, the model deliberately distinguishes between incoming spillovers, $b(B)$, and outgoing spillovers, $a(P)$, endogeneizing both. On the one hand, the incoming spillovers $b(B)$ indicate the access the innovating firm has to external knowledge through investments in basic research $B$. On the other hand, the outgoing

[10] Including in the model the possibility that legal protection R would without strategic investments $P$ at least partially be able to prevent diffusion, i.e. $a(P) = 1 - [(1+R)(1+ P)^{p}]$, seriously complicates the model but would still generate a positive effect of $R$ on $P$.

[11] To compare in the total sample of innovative firms, the % of firms who rate strategic protection as at least moderately important is 65% (of high to crucially important, 28%). The chisq test is significant at 1%.

spillovers $a(P)$ represent the loss of returns because of information flows to imitators. Investments in protection, $P$, affect these flows. Furthermore, the model allows us to discuss the decision on the size of the budget and its allocation over $A$, $B$, and $P$ in different steps. First, we look at the optimal total budget to spend on Technology $T$. Second, given $T$, how much to spend on the creation of know-how, $I$ and on the protection of this know-how $P$. Third, given the investments accruing to know-how creation $I$, how does the firm allocate it between applied and basic research, $A$ and $B$, with the latter allowing the firm to access external know-how.[12] The following table summarizes the model set-up:

(1) $\max_{T} \; P(T)$

s.t. $T \geq 0$,

where $P(T) = N \, \Delta s(T) - T$.

$\Delta s(T)$ is the value function of (2):

(2) $\max_{I, P} \; \Delta s(I, P)$

s.t. $I + P = T$; $I, P \geq 0$,

where $\Delta s(I, P) = (1 - a(P)) \, X(I) = (R + 1) \, P^{p} \, X(I)$.

$X(I)$ is the value function of (3):

(3) $\max_{A, B} \; X(A, B)$

s.t. $A + B = I$; $A, B \geq 0$,

where $X(A, B) = [A^{a} \, (1 + b \, K \, B)^{b}]$.

[12] A possible interpretation of the model set-up, consistent with the decentralization within large companies is the following. The HQ decides on the total expenditure on technology. Next, the strategic decision on the share between creation of know-how and its protection is taken. Finally, the R&D department decides the best allocation between applied and basic research. Note that this is only an interpretation, the resolution of the previous three steps provides the optimal decisions on $A$, $B$, and $P$ in the maximization program where the firm chooses (simultaneously) optimally $A$, $B$ and $P$.

## *3. Model Results*

### 3.1. Applied versus Basic Research

We start with the discussion on the allocation of the R&D budget between basic and applied research, *A* and *B*, for a given budget size *I*. Although the resulting expressions for levels of *A* and *B* are not yet equilibrium levels before we have solved all steps of the model (see Section 3.3), they are nevertheless interesting to discuss since they reflect the short-term position of a research department when faced with a budget constraint.

| | |
|---|---|
| (3) | $\max_{A, B} [A^a (1 + b K B)^b]$ s.t. $A + B = I$; $A, B \geq 0$. |

The optimal value for the endogenous variables $A(I)$ and $B(I)$ and the value function $X(I)$ can take two expressions depending on the level of the budget $I$:

Let $I^* = \dfrac{a}{bbK}$,

(i) if $I \leq I^*$: $A(I) = I$,

$B(I) = 0$,

$X(I) = I^a$;

(ii) if $I > I^*$: $$A(I) = \frac{a(bKI + 1)}{(a+b)bK}$$

$$B(I) = \frac{b(bKI + 1)}{(a+b)bK} - \frac{1}{bK}$$

$$X(I) = \left[\frac{(bKI + 1)}{(bK)^a}\right]^{a+b} \frac{a^a b^b}{(a+b)^{a+b}}$$

Note that $X(I)$ is twice differentiable in $I$ (although the second derivative is not continuous at the point $I^*$).

A leading firm with a small budget *I* cannot afford to spend on basic research. This follows from the complementary nature of basic research. On its own, basic research will not result in effective know-how, giving rise to improvements in product quality. Building up effective know-how always requires applied research. If the budget is too small, the priority goes to applied research. If however, the leading firm's budget on $I$ is sufficiently large, the firm will be able to devote resources to basic research which will allow it to tap the pool of relevant external know-how available, $bK$. The larger this pool of relevant external know-how, the smaller the threshold level of investments $I$ required to start spending on basic research.

Interesting to note is that the ratio of basic to applied research will increase with the budget $I$, once the firm starts investing in basic research.

$$\frac{B(I)}{A(I)} = \frac{b}{a} - \frac{a+b}{a(bKI+1)}$$

The more the leading firm will spend on R&D, the larger the share that goes to basic research. This result is in line with the empirical observation that basic R&D is typically more associated with big firms with large R&D budgets. Basic research, as a way of accessing external know-how, becomes increasingly more productive when combined with larger amounts of applied research. Although applied research also becomes more productive when combined with larger amounts of basic research, this effect is less predominant than the previous one, given the head-start for applied research.

As the pool of accessible and relevant external know-how, $bK$, increases, a leading firm, given a fixed budget, will invest a higher fraction of its budget in basic rather than applied research. In total, a firm's effective know-how base, $X$, will go up when a larger external know-how base is available, for a given budget $I$.

### 3.2. Protection versus Creation of know-how

A next step in the analysis is the allocation of the total budget on Technology Investments, between the creation of know-how through basic and applied research, and the protection of this know-how, i.e., the allocation between $I$ and $P$, given $T$. The optimal decision is considered in the following program:

$$\text{(2)} \qquad \max_{I,P} \; (R+1)\, P^{p} X(I) \quad \text{s.t.} \quad I + P = T; \;\; I, P \geq 0.$$

Denoting $T^* = \frac{a+p}{bbK}$, again we have two cases:

(i) if $T \le T^*$:

$$I(T) = \frac{a}{(a+p)} T,$$

$$P(T) = \frac{p}{(a+p)} T,$$

$$\Delta s(T) = (R+1) \frac{a^a p^p}{(a+p)^{a+p}} T^{a+p}.$$

Note that in case (i), $I \le I^*$, see section 3.1. In particular, the optimal investments in applied and basic research in this case are:

$$A(T) = \frac{a}{(a+p)} T \quad \text{and} \quad B(T) = 0.$$

(ii) if $T > T^*$:

$$I(T) = \frac{a+b}{(a+b+p)} T - \frac{p}{(a+b+p)} \frac{1}{bK},$$

$$P(T) = \frac{p}{(a+b+p)} T + \frac{p}{(a+b+p)} \frac{1}{bK},$$

$$\Delta s(T) = (R+1) \frac{a^a b^b p^p}{(a+b+p)^{a+b+p}} \frac{(bKT+1)^{a+b+p}}{(bK)^{a+p}}.$$

The optimal investments in applied and basic research in case (ii) are:

$$A(T) = \frac{a}{(a+b+p)} T + \frac{a}{(a+b+p)} \frac{1}{bK}, \text{ and}$$

$$B(T) = \frac{b}{(a+b+p)} T - \frac{(a+p)}{(a+b+p)} \frac{1}{bK}.$$

Up to the critical budget level *T**, the leading firm doesn't spend on basic research. As $T < T^*$, firms increase their expenditures on creation of know-how (through applied research only) and on protection of know-how in a linear fashion with increases in T.

Once the budget for technology investment grows beyond the critical level *T**, firms start spending on basic research. Larger budgets will lead to increases in applied and basic research, as well as in investments in protection. Applied research will increase less with increases in the budget *T* in case (ii) than in case (i), but total investments in the creation of know-how *I*, including basic research, will increase more with larger budgets in case (ii) than in case (i).[13] The opposite holds for expenditures on protection of know-how: beyond $T^*$ expenditures on protection *P* will increase with larger budget available to a smaller extent than before $T^*$. All this implies that the allocation of expenditures between creation and protection will increasingly favor creation over protection with larger budgets available. These relations are illustrated in Figure 1.

*- Insert Figure 1 here -*

Even if the ratio $P/I$ between the expenditures in protection and creation decreases with the budget *T*, the ratio between protected know how and created know how $\Delta s/X$ (which is the complement to the diffusion rate $(1 - a(P))$) increases with the budget. That is, a larger budget favours actual protection over actual creation.

### 3.3. Optimal Technology Investments

We finally turn to the decision on the optimal size of the budget for technology investments, *T*. This is a strategic decision a firm faces in the medium to long-run, when investment budgets become choice variables. The firm solves:

$$(1) \quad \max_{T} \{N\,\Delta s(T) - T\}$$
$$\text{s.t.} \quad T \geq 0.$$

Note that the objective function $P(T) = N\,\Delta s(T) - T$ is continuously differentiable, and it has a negative second derivative (the second derivative is discontinuous at the point $T^*$).

Again we have to distinguish two cases. Depending on whether *T* is smaller or larger than $T^*$, we have a different expression for the value of $\Delta s(T)$, see section 3.2. The optimal total investment *T*, as well as the optimal values of the different investment decisions of the firm are the following:

[13] This is because $(a+b)/(a+b+p) > a/(a+p)$.

Let $V = \left[N(R+1)a^{a}p^{p}\right]^{\frac{1}{1-a-p}}$, and, $W = \left[N(R+1)a^{a}b^{b}p^{p}(bK)^{b}\right]^{\frac{1}{1-a-b-p}}$.

(i) if $W \le \frac{1}{bbK}$:

$$T = (a+p)V,$$

where $A = I = aV$ and $B = 0$,

$$P = pV.$$

(ii) if $W > \frac{1}{bbK}$:

$$T = (a+b+p)W - \frac{1}{bK},$$

$$I = (a+b)W - \frac{1}{bK}, \text{ where } A = aW \text{ and } B = bW - \frac{1}{bK},$$

$$P = pW,$$

The leading firm needs to spend on applied research to keep a quality edge over its rivals in the fringe. At the same time the firm needs to spend on protection to prevent diffusion to these fringe firms. Whether or not the leading firm spend on basic research depends on the size of the market,[14] on the effectiveness of legal protection, and, on the pool of accessible and relevant external know-how.

In Case (i)—no spending on basic research—the increase in market attractiveness *N* will boost technology spending *T*, both on the creation and the protection of know-how. Better legal protection provides a similar incentive for more spending on *T* (both *A* and *P*). Both of these drivers will not change the ratio of spending on creation versus protection, as long as the firm is not accessing external know-how.[15]

When the leading firm starts accessing external know-how (Case (ii)), the allocation decisions look different. The firm will start spending on basic R&D, which allows it to access the pool of external know-how. Market attractiveness *N* and legal protection *R* will stimulate spending on creative as well as on protective investments, as in case (i). But we now also have basic research as a complementary way to create effective know-how. The ratio of basic to applied research in creating own know-how

[14] Note that market size *N* has two components: the size of the market in terms of number of customers, *M* and the willingness to pay for quality (increments), $q_h$.

will be larger when the leading firm faces more attractive markets (N) or better legal appropriation regimes (R).[16] An increase in *N* or *R* furthermore leads to a higher ratio of actual protection $\Delta s$ over actual creation *X* while increasing the value of investment in *P*. [17] Our model thus generates complementarity between exogeneously given legal protection, R, and optimal investments in strategic protection P.[18]

The availability of external know-how will only influence the leading firm's investment decision once it invests in basic research, i.e. in case (ii). It is clear that in our model a larger pool of accessible external know-how (either by a larger pool *K* or a more accessible pool, *b*) will lead to more spending on technology, both in creating internal know-how as in protecting this newly created own know-how base. Increases in expenditures on the creation of own know-how due to a larger pool of accessible external know-how establishes that internal and external know-how are complementary. External know-how stimulates not only internal basic research which is needed to access the pool, but it will also make applied research more productive and hence increase spending on the latter as well. Expenditures on basic research will be larger, the larger is the pool of accessible know-how, *bK*, not only because of its access-function but also because of its function of leveraging the efficiency of applied research. All this implies that the ratio of spending on basic versus applied research is typically larger when larger pools of accessible know-how are available, although at a decreasing rate[19]. The increase in spending on basic research also induces the ratio of spending on creation versus protection to increase with the pool of accessible know-how. However, because of the effect of *X* on $\Delta s$, the ratio of protected versus created know-how also increases with *bK*.

In conclusion, the model generates clear-cut hypotheses on the allocation of investments over applied and basic research and protection. These hypotheses can be tested empirically if data on expenditures are available.[20] The optimal levels of

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[15] This ratio is only affected (positively) by the efficiency parameter of the R&D technology $a+b$ and (negatively) by the parameter of the efficiency of the protection technology $p$. ($I/P = (a+b)/p$)

[16] This increase in the *B/A* ratio is decreasing in *N* and *R*, given a negative second order effect.

[17] It can be shown that the increase of investments in *P* due to *R* (or *N*) is larger in case (ii) than in case (i).

[18] Relaxing this assumption as in footnote 9 could lead to P = 0 for small values of *N*, *R* and *bK*.

[19] This increase in the *B/A* ratio is decreasing in *bK* given a negative second order effect

[20] Unfortunately, the CIS/EUROSTAT data do not provide us with quantitative data on technology expenditures in each category, i.e. on applied and basic research, and on investments made on protection. It only provides indirect evidence on the importance of different information sources for innovation and the effectiveness of protection mechanisms.

investment *A*, *B*, and *P* are increasing in market attractiveness *N*, the effectiveness of the legal appropriation regime *R* and (weakly) increasing in volume of accessible external information *bK*. Therefore, total investment in technology should be positively related to these variables. The comparative statics results show a discontinuity at a cutoff which determines whether or not the firm invests in basic research. The cutoff is more likely exceeded for higher values of *bK*, *N* and *R*. In addition, and perhaps more interestingly, the theoretical model presents some clear predictions on the ratio of expenditures of applied R&D to basic R&D. The ratio of applied-to-basic research was found to decrease in the volume of accessible external information, *bK*, the tightness of the legal appropriation regime, *R*, and, the size of the market, *N*. In particular, the most obvious prediction is on access to external information. For large values of this variable, the firm's basic research should be relatively more stimulated than its applied research expenditures. A more efficient legal protection system, R, results in a significantly higher ratio of protected-to-created knowledge, *Ds*/X or 1- *a*(*P*). This confirms the complementarity between the efficiency of legal protection and the incentives for firms to engage in strategic protection. The results further reveal a link between incoming and outgoing knowledge flows: the positive effect from *bK* on *P* and, hence, on the ratio of protected-to-created knowledge, suggests that firms for which external information is more important, will also consider protecting their know-how as more important.

### 3.4. Discussion and Extensions

*a) Intellectual property rights protection*

An important technology policy instrument in many countries is the protection of intellectual property rights through the patent system. The aim of the patent system is to stimulate inventions and investments to develop and commercialize innovations. This is also the result in our model. A legal system that is more efficient in protecting intellectual property, i.e. a larger *R*, will stimulate technology investments, *T*. But more interestingly, the model also allows us to discuss the effect on the allocation of these investments. First, there is a positive effect on defensive investments to protect know-how, which are more efficient the better the legal system. Although these defensive investments may not be interesting from a -technological progress-point of view, they are nevertheless important. Indeed, because of the better appropriability, firms will also invest more in the creation of know-how, not only through own applied research, but firms will also have a larger incentive to tap into existing know-how by investing in basic research. Our results suggest that the effect on the creative investment is more important than on the protection investment. The creation of know-how will be biased towards basic research, at least for firms/economies that are sufficiently innovation-active, in that they are capable of accessing external know-how through basic research.

The patent system, by granting temporary monopoly rights to the innovator, is not only designed to stimulate innovations. At the same time, it invigorates diffusion by specifying property rights and making the technical information embedded in the patent publicly accessible.[21] In terms of the model specification, this would imply a larger accessible external know-how base through $b$.[22] A better diffusion power of the patent system will only have an impact on firm's innovative strategies if they are investing in basic research to access external know-how. In this case any improvement in the distributive power of the patent system will again result in more spending on basic and applied research as well as on protection. Nevertheless, investments in basic research will be favored in relative terms.

*b) R&D Cooperation*

When devising their innovation strategies, organizations rely increasingly on cooperative R&D agreements. Firms expose, transfer, and develop valuable know-how within these cooperative R&D ventures. The relationship between R&D cooperation and R&D spillovers is relatively well developed in theoretical models, see Cassiman & Veugelers (1999) for a review. While most models study how the level of spillovers influences the decision of a firm to cooperate in R&D, the decision to cooperate also affects the level of spillovers in an important way. On the one hand, a cooperative agreement increases incoming spillovers. This might be the result of information sharing between partners, as in the RJV scenario in Kamien et al. (1992). Cassiman & Veugelers (1999) provide empirical evidence for the positive association of incoming spillovers and R&D cooperation. On the other hand, a cooperative

[21] Indeed patent information is one important source of publicly available information in the CIS data.

[22] Note that this does not necessarily imply an increase in $\alpha$, the diffusion to the fringe, because these firms are not innovation active. If the patent would for example reveal product specifications that the fringe could copy, then the legal protection of the patent system would not have become more efficient in protecting intellectual property.

agreement increases the probability of spillovers to outside firms because of this information sharing. However, Cassiman and Veugelers (1999) find that partners in a cooperative agreement also have more effective protection against outgoing spillovers. They thus find evidence that firms actively manage information flows through cooperation, i.e. maximizing access to external information sources as well as protection of own information. Furthermore, the type of research partner is important in understanding these effects. In cooperative agreements with research organizations or universities, influencing *incoming* spillovers is important. When cooperating with suppliers or customers, partners also worry about minimizing the *outgoing* spillovers.

Incorporating these results into our model allows us to study how R&D cooperation, through its impact on in- and outgoing knowledge flows, will influence the nature of the firm's innovation strategy. First, it is important to note that in our model, there is no incentive for the leading firm to team up with competitors in a cooperative R&D agreement: fringe firms are not innovation active and their know-how base is completely derived from the firm's own know-how base. We will hence ignore intra-industry cooperation with competitors.[23] The impact of inter-industry joint ventures can be interpreted as a comparative statics exercise on the (accessibility of) external know-how $bK$. Either know-how is transferred among cooperating partners ($bK$) or the efficiency of research is increased through realizing economies of scope in innovation by combining complementary innovative capabilities (affecting $a$ *and/or* $b$). Therefore, the model predicts that collaborating firms will spend more on protecting know-how, as well as on creating know-how, both through more applied research and through more basic research. Furthermore, the ratio of basic to applied research, and the ratio of creation versus protection investments, will be larger for cooperating firms. In addition, the ratio of protected over created know how will be larger for cooperating firms. This view of R&D cooperation is very much in line with the findings in Lim (2000) on the relation between connectedness and absorptive capacity where relationships with universities and membership of R&D consortia are the main drivers of connectedness.

Different types of partners –suppliers or customers versus research institutes- will imply a different impact of R&D cooperation on the relationship between knowledge

[23] Note that in empirical observations, cooperation with competitors is only a minor phenomenon as compared to cooperation with suppliers, customers or independent research institutes (see Cassiman &Veugelers (1999)).

flows and the firm's innovative decisions. By collaborating with research institutes, firms can improve the technological know-how transfer, increasing the (efficiency of the) pool of accessible external know-how *b*K and/or the parameter *b*, the efficiency of basic research. Teaming up with clients or suppliers allows the firm to tap more efficiently into a highly relevant source of external know-how. Given the nature of these cooperative agreements, they could also increase the R&D efficiency of applied research, *a*, rather than the basic research efficiency, *b*. But a joint venture with vertically related partners will not only allow to increase the (efficiency of) know-how, it also introduces a danger of reducing appropriability. This is reminiscent of the idea that competitors learn about their rivals through common suppliers or customers. It implies that firms cooperating with common suppliers or customers, might find it more difficult to appropriate their know-how, i.e. a lower value for the *p*-parameter. Typically innovative investment will decrease with lower values of *p*, both in the protection and the creation of know-how.[24]

c) Extensions

The main objective of this paper is to build a model that carefully considers knowledge flows to and from firms while at the same time is simple enough to allow for a complete analysis of its properties. We have made several simplifying assumptions to be able to reach this goal. In what follows we discuss the effects of relaxing some of the assumptions on the main results.

First, we make the assumption that basic research only helps absorptive capacity (and has no direct productive effect) and that the reverse is true for applied research. In fact, the previous characteristics are our definitions for the two types of research. In the empirical literature, however, the relationship is not so clear cut. For example, Griliches (1986) and Mansfield (1980) report positive rates of return on basic research within firms and Lim (2000) suggests that applied research (and connectedness) may be as important as pure basic research for absorptive capacity. Clearly, our main results do depend on the way we model the relationship between the two types of research. But, we do think that the most important difference between basic and applied research is the much larger absorptive capacity of the first versus

[24] Reduced appropriability when captured through the *p*-parameter would reduce the incentives for firms to invest in protection. However, reduced appropriability through a higher level of exogenous

the second type. However, the main properties of the optimal investment, in particular the ratio between applied and basic research, remain if we allow for the possibility that basic research is useful in itself according to the following function for the created knowledge:

$$X_L = A^a\ [1 + B\,(s + b\,K)]^b,$$

where $s$ represents the extent to which basic research allows creating knowledge without external know-how. Lim (2000) observed that in the pharmaceutical industry most firms do a significant amount of pure basic research. In the semiconductor industry only a few firms are engaged in pure basic research, but all firms make significant investments in absorptive capacity through connectedness (which he calls applied research). In terms of our models s = 0 in the semiconductor industry, while s > 0 for the pharmaceutical industry.

Second, we assume that the outside knowledge $bK$ is captured by the investment in basic research in a linear fashion. (Notice, however, that the total effect is not linear in our framework due to the parameter $b$.) The linearity hypothesis matters in order to be able to solve the model; otherwise one cannot go further than solving the last step (program (3)). Take, for example, the function

$$X_L = A^a\ [1 + b(B)\ K)]^b,$$

where $b(B)$ is any function. Both, the existence of a region of (low level of) investments in which no basic research is performed and the result that the ratio basic versus applied research is increasing in the investment once the firm invests in basic research still hold for this generalization of the model if the investment level is not too high. If the function is $b(B)$ is concave and the level of investment is very high, there exists a point from which the ratio will decline onwards.

Finally, an important characteristic of our model is that we consider a leading firm in an industry facing a competitive fringe. The hypothesis that only one firm invests in R&D is a simplification that may not be important in some markets. As we

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diffusion, as captured by an exogenous shift in $\alpha$, would increase the necessity for protective investments.

already pointed out, most innovation-active firms see themselves as leaders or at least among the leading companies in their industry. In other markets the hypothesis that only one firm invests is clearly a restriction. We discuss here the effects of the existence of technological competition among several firms on our results.

Competition among firms has two broad effects on the firms' investments. First, it strongly influences the level of such investments. This is the objective of analysis of many papers in the R&D literature, starting from the seminal paper by Arrow (1962). Given the level of technology investments, our results on the relative allocation between applied research, basic research and protection remain valid. Our contribution is, therefore, not in this line of research although we think that the framework that we propose can be the starting point for some further research in this area.

The second effect of competition concerns the distribution of the investment level between the different types: basic and applied research and protection. As long as the diffusion from a firm to its competitors is dependent on the level of created knowledge (X) of the firms but not on the source (applied or basic) of research that generated this knowledge, the main results concerning the relationship between applied and basic research hold independently of the existence of competition. Basic research is only financed if the level of investment is high enough, and the ratio basic to applied is increasing in the investments. These conclusions where already obtained when solving the last step of the model (program (3)), which looks at the optimal sharing of the investment between the two possible types of research given the level of the budget for research (I). Similarly, the firm learning from its competitors would not alter our results as long as learning is related to the created knowledge of these competitors. In that case a simple comparative statics result on $\beta K$ provides the result. The sharing between protection and creation, however, will be influenced by competition if the effectiveness of the protection technology is small when other technologically advanced firms compete in the market. The analysis in Section 3.2 seems to suggest that a decrease in the effectiveness parameter $p$ would decrease the investment in protection, for a given $I$. This conclusion is however misleading since, first, the optimal investment decision will certainly be affected by competition, and second, the profit function of a firm would not only be affected by the distance between the technologies (as in our simple framework) but would be a more complex function of the technologies at hand by the competing firms. The analysis of these trade-offs is beyond the scope of the present paper.

## Conclusions

In this paper we carefully model the interactions between knowledge flows on the one hand and firm's innovation decisions on the other hand. Firms will attempt to affect the impact of incoming and outgoing knowledge flows to and from the firm through their decisions on the size and nature of R&D activities undertaken. Three investment activities are distinguished: investments in applied research, investments in basic research, and investments in intellectual property protection. The market structure is one where a firm is facing a fringe of followers, producing a product differentiated in quality. The leading firm uses its effective knowledge base to improve the quality of the product. This knowledge base is built by combining internal and external know-how. Only when basic research is performed, can the stock of relevant and accessible outside know-how be used effectively. It may then serve to increase the efficiency of own applied research. The process of diffusion is partly exogeneous, affected by the effectiveness of legal protection or the appropriability degree of the technology. But the firm can also influence the ease of imitation by investing in protection.

The theoretical model shows that firms with small budgets for innovation will not invest in basic research. This occurs in the short run, when the budget on know-how creation is restricted, or in the long-run, when market size is too small, when legal protection is not very important, or when the pool of accessible and relevant external know-how is restricted. Once firms start accessing external know-how by spending on basic research as a way to create effective know-how, the ratio of basic to applied research will increase, the more firms spend on R&D. This could happen because of a larger pool of accessible external know-how that, overall, will lead to more spending on technology, both in creating internal know-how and in protecting this newly created own know-how base. Similar effects are present in larger markets or markets with a higher willingness to pay and in markets where intellectual property rights protection is tighter. Therefore, our model can explain the complementarity between internal and external sourcing, through the interactions between basic and applied research, as well as the complementarity between legal and strategic protective technology investments. In addition, it establishes increasing returns to basic research as a consequence of external factors such as the size of the market, the extent of the pool of external knowledge available to the industry, and the effectiveness of intellectual property rights protection, rather than the more traditional explanation of economies of scale in basic research because of the minimum efficient scale of a research department.

The simplifications in the current model allow to trace explicit analytical results on optimal technology budget allocations, while generating predictions that seem to corroborate with some stylized facts. It remains to be investigated whether the results extend to more general settings, for instance with respect to market structure and diffusion regimes. Since the integration of protective and creative motives in innovation strategies is underdeveloped in the literature, we hope by presenting our theoretical model, to stimulate further theoretical and empirical research on this topic.

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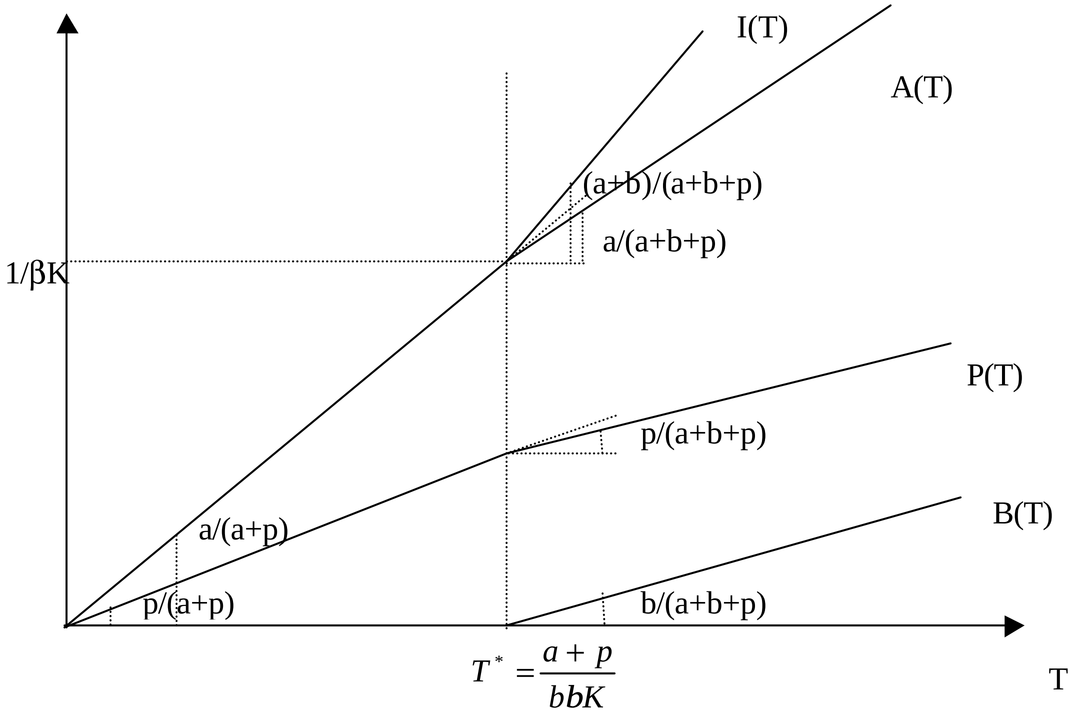


- Figure 1 :Optimal allocation of Technology Investment T into A, B, P -

Note: Picture is drawn for a>p