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Innovation and Bureaucracy Under Soft and Hard Budget Constraints

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Because of the inherent uncertainty, promotion of innovation critically depends on screening mechanisms to select projects. This paper studies the relationship between bureaucracy and financial constraints as two such mechanisms. The lack of commitment to hard financial constraints interferes with its *ex post* screening capability; *ex ante* bureaucratic screening is optimally chosen as a substitute. However, bureaucracy makes mistakes by rejecting promising projects and delays innovation, and the efficiency loss due to soft financial constraints increases as prior knowledge becomes worse and as research stage investment requirements become lower. In a centralized economy, bureaucracy may reduce the number of parallel projects, particularly for projects with higher uncertainties and less research stage requirements. This theory fits much of the evidence and in particular it explains why the computer industry, but not the nuclear or aerospace industries, has fared so poorly in centralized economies.

1. INTRODUCTION

The fundamental importance of innovation to the survival and evolution of economic systems and organizations has long been recognized (Marx (1978), Schumpeter (1950)). Innovation is characterized by its inherent uncertainty because it is "a process whose every element takes considerable time in revealing its true features and ultimate effects" (Schumpeter (1950), p. 83), and people are unable "to anticipate the future impact of successful innovations, even after their technical feasibility has been established" (Rosenberg (1994)). An understanding of how different systems and organizations deal with the uncertainties associated with innovation and the resultant consequences is crucial for understanding alternative economic systems and organizations.

In this paper, we provide a theory to analyse how different systems screen uncertain innovative projects and the impact of the various screening mechanisms on those systems. We distinguish two alternative screening mechanisms: the bureaucratic screening mechanism vs. the market screening mechanism. The latter is directly linked to financial constraints. With this perspective, our theory explains why centralized economies did well in certain areas of innovation but fared poorly in others. For instance, in the early 1960s the West was frightened by the USSR's great success in launching the first unmanned satellite and the first manned space capsule; while in the 1980s, in contrast, the centralized system failed miserably to develop computers which were the core of the "Star Wars" programme. Our theory is also relevant for an understanding of the impact of various financial institutions on innovation in a market economy; for instance, why R&D in small firms financed by venture capitalists enjoys an advantage in highly uncertain innovative projects, while R&D in large corporations has an advantage in less uncertain projects.

In our model we capture the intrinsic uncertainty in innovation by introducing both the cost and outcome uncertainties of innovation. Before conducting a project and before pre-screening, no one knows the exact costs or the final outcome of the project: the information is (symmetrically) imperfect for both the investors and the innovators. During the research and development stages, more and more investments are sunk, and information is gradually revealed to the innovators and the investors in an asymmetric way. Our model then applies the contractual foundation provided by Dewatripont and Maskin (1995), where the centralized economy (i.e. all projects are financed and refinanced through the state) is subject to soft budget constraints, that is, high-cost projects cannot be terminated *ex post*; in contrast, the decentralized economy (i.e. projects are financed by many financial institutions) leads to hard budget constraints under which high-cost projects are terminated *ex post*.

With this setup, we study the relationship between the bureaucratic screening and the market screening mechanisms. We argue that while the *ex post* market screening mechanism to terminate high-cost projects is a valuable mechanism,[1] the bureaucratic pre-screening mechanism is an alternative mechanism to screen out high-cost projects *ex ante*. However, the effectiveness (or ineffectiveness) of the pre-screening mechanism depends on several factors. Our approach allows us to address the following important questions, most of which have not been adequately acknowledged by the literature: (a) What accounts for the differences in innovation between centralized and decentralized economies? (b) Why do bureaucracies approve fewer than the optimal number of parallel research projects? And (c) given that bureaucracies seem to perform poorly in selecting innovations, why did centralized economies nevertheless still rely on them so heavily?

We show that compared with *ex post* market screening, bureaucracy can work well when prior knowledge is good (for example, in the case of the aerospace industry where the relevant physics principles were well understood from the outset), but does not work when prior knowledge is bad (in the case of the computer industry where the necessary principles of computer science and solid state physics were developed simultaneously with or even after the earlier generations of electronic computing machines) (Propositions 3 and 6). Moreover, the impact of the soft budget constraint is small when the research-stage investment requirement is relatively high (for example, aerospace projects require huge funding to start up), but it is very serious when the research-stage investment requirement is relatively low (for example, computer technologies which demand much smaller funding at the beginning stages) (Propositions 4 and 7). In summary, our theory predicts that the gap in innovation performance between centralized and decentralized economies will be particularly large for such industries as that of computers.[2]

Moreover, our theory bears on our understanding of different types of organizations in dealing with different kinds of innovations. Given that large corporations have softer

1. In decentralized economies, "the vast majority of attempts at innovation fail" due to the inherent uncertainty in innovation (Rosenberg (1994)). People in Silicon Valley often say the great secret of their success is their willingness to let projects fail.

2. Our paper, in the spirit of Kornai (1980), emphasizes the problems arising from the relaxation of financial constraints. In contrast, most finance literature focuses on the difficulties of financing through dispersed or conflicting investors (see, for example, von Thadden (1995)).

budget constraints than small firms—particularly venture capital firms—our theory predicts that large corporations may rely more on bureaucratic pre-screening, and they may do better in innovative projects with fewer uncertainties and large research-stage investment requirements. In particular, large corporations are very demanding in funding small projects: the financial appraisal standards applied to small projects are often significantly higher than those applied to large projects. In contrast, small firms financed with venture capital may have advantages over large corporations for more uncertain projects with poorer prior knowledge or a higher probability of failure, or for projects requiring smaller initial funding. Thus, idea-rich small firms originate a disproportionate share of innovations.

Almost all existing theories on innovation in centralized economies blame the failure of innovation on the lack of incentives for potential innovators: managers do not receive adequate rewards to compensate them for risk-taking (Hayek (1945)); the practice of "taut planning" for routine operations induces risks for undertaking innovation (Berliner (1976)); chronic shortages permit state-owned enterprises to sell everything too quickly (Kornai (1980)); and the "ratchet effect" makes the cost of adopting innovation too high (Dearden, Ickes and Samuelson (1990)). However, none of these theories predict much difference in the way that a centralized economy handles different types of projects. Thus none of them can explain the empirical evidence described above. Because we endogenize bureaucracy as an organizational response to the problem of the lack of *ex post* screening mechanisms, we are able to explain why industries in centralized economies perform differently.

We view the use of bureaucratic screening as an organizational response to the failure of the market screening mechanism, and our analysis contributes to the emerging endogenous theory of bureaucracy. Tirole (1986) argues that rigid bureaucratic rules are a method to prevent collusion among agents. Milgrom (1988) emphasizes that these rules are a rational way of curbing detrimental influence activities of agents in organizations. Holmstrom (1989) argues that large firms are in favour of routine tasks rather than innovation because the internal evaluation of the former is relatively easier; also, large firms need to raise capital from the stock market which may discourage undertaking long-term risky projects. Bolton and Farrell (1990) argue that for urgent tasks (e.g. wars or other emergencies), centralization is more desirable under the condition that coordination is essential and cost considerations are unimportant. Sah and Stiglitz (1986, 1988) compare decision-making errors under hierarchies, polyarchies, and committees.

The paper is organized as follows. Section 2 introduces the model. Sections 3 analyses the relationship between *ex ante* bureaucratic screening and *ex post* commitment to terminating high-cost projects when the returns of projects are additive. Section 4 studies parallel research in the case of non-additive returns. Section 5 discusses innovations in large and small firms in decentralized economies.

2. THE MODEL

A fundamental feature of innovation is uncertainty from imperfect information about the future benefits and costs of innovative projects. In our model there is a double (but independent) uncertainty concerning the cost and outcome of innovative projects. On the cost side, a project can be either a low-cost type or a high-cost type, due to both technical and economic reasons. Assume that the probability of a project being low cost is α and that of high cost is $1-\alpha$. For both low-cost and high-cost projects, conditional on the completion of the project, the project will succeed and generate revenue R with probability

p; it will fail and generate no revenue with probability $1-p$. We define a successful outcome as both technical and economic success, and an outcome of failure as either a pure technical failure or a technical success but an economic failure.

Although neither the investor nor the innovator knows about the exact cost or the outcome of any particular project before it starts ("it is too early to know"), there exists some prior scientific, technological, and economic knowledge about the project which is contained in some signals. We assume that by spending time in collecting information, such as consulting experts, holding committee meetings, etc., investors are able to observe a signal θ for cost type. The relationship between the signal and underlying true state of nature is represented by the following probability matrix:

	θ^L	θ^H
low cost type	γ	$1-\gamma$
high cost type	$1-\gamma$	γ

where $\frac{1}{2} \leq \gamma \leq 1$. Therefore θ^L speaks for low-cost type and θ^H for high-cost type.

An innovator with an idea has no funds so he must go to investors for financing to carry out the research and development. The time line of the model is depicted in the following figure.

Time:	date 0	date 1	date 2	date 3	date 4
Stage:	pre-screening	research	development	further development	
Investments/returns:		$-I_1$	$-I_2$	$-I_3$ or 0	R or 0
Information:	prior knowledge		cost resolved to innovators	cost resolved to investors	realized outcome

At date 0, the investors decide whether to receive the signal θ for pre-screening. In the case of the centralized economy, the pre-screening corresponds to bureaucratic approval of the project. In the case of small firms in the decentralized economy, pre-screening is conducted either by the investors or by some specialized agencies.[3] For simplicity, we assume that observing θ takes one period of time and needs no other resources. The cost of delay is captured by the discount factor δ ($0 \leq \delta \leq 1$). Should the investors choose not to pre-screen the projects, they will not be delayed.

At date 1, each of the approved projects requires I_1 units of capital to start (research stage). The innovator acquires knowledge during research stage, the period from date 1 to date 2, about the type of the project he is endowed with, but the investors still do not know the type. Asymmetric information arises at date 2: at date 2, both types of projects require I_2 units of capital to continue (development stage).[4] If the innovator with a high-cost type project chooses to stop at this time, the private benefit accruing to the innovator is assumed to be zero.

A low-cost type project is completed at date 3 and generates discounted revenue R if it is a success and 0 if it is a failure. Upon completion of the project, the innovator receives expected private benefits equal to $B_L > 0$. A high-cost type project has a delayed completion. The return of a high-cost type project at date 3 is very low and for simplicity is assumed to be zero. If the project is terminated at this time, the private benefit accrued to the

3. The credit-worthiness test in the presence of market competition is discussed in detail in Broecker (1990).

4. The Dewatripont-Maskin model starts from asymmetric information, which is similar to date 2 in our model. With two more periods in the model, we study information revelation through pre-screening and carrying out one period of research.

innovator is equal to $B_l < 0$. Therefore, if a high-cost type project must be terminated at date 3, the innovator will end it at date 2 to avoid a bigger loss.

The cost type of a project is revealed to the investor at date 3. If additional investment I_3 is made in the high-cost type project at this time (further development stage), then the project completes at date 4 and generates revenue R if it is a success and 0 if it is a failure. The expected private benefit accruing to the innovator at date 4 is equal to $B_H > 0$. Hence, as long as a high-cost type project is not terminated at date 3, an innovator wants to make use of every idea at date 0.

We make the following assumptions regarding the investment expenditures and returns underlying innovative projects:

Assumptions.

(i) $pR > I_1 + I_2 + (1-\alpha)I_3$;
(ii) $pR < I_2 + I_3$; and
(iii) $pR > I_3$.

Assumption (i) says that the mix of high-cost and low-cost projects has positive expected net present value, which assures that a project starts even without any screening mechanism. Assumption (ii) states that the high-cost type project is bad *ex ante* in the sense that it has a negative expected present value at the time the type of the project becomes known to the innovator. Assumptions (i) and (ii) together requires $I_1/I_3 < \alpha$, that is, the cost of the last stage refinancing should be high relative to the cost of the first stage financing. Since what matters here is the ratio, not the absolute size of I_1 or I_3, this inequality can be held to any project, big or small. Assumption (iii) implies that it is *ex post* efficient to refinance a high cost project ("it is too late to stop").[5]

We give all the bargaining power to the investors so that the innovators' returns are limited to their private benefits. In a centralized economy, all financial resources are controlled by the state. According to Assumption (iii), once a high cost innovative project is financed at date 1 and date 2, it will be refinanced at date 3 because, given that the first two stage investments are sunk, it is *ex post* efficient to do so. Foreseeing this, an innovator with a high cost project has no incentives to stop at date 2 when he obtains that information, because the private benefits accruing to an innovator are positive when the project is completed. Therefore, in the centralized economy, because the state is unable to make a credible commitment not to refinance high-cost projects, all high-cost projects are started, refinanced, and completed. This corresponds to the "soft budget constraint."[6]

In a decentralized economy, there are many dispersed investors and/or financial intermediaries. Following Dewatripont and Maskin (1995), we assume that each investor is relatively small, in the sense that when it comes to refinancing, either he runs out of funds or he faces a liquidity constraint—funds are tied up with other projects. In order to refinance, at date 3 the old inside investor, who monitors the project in earlier periods, has to go to a new outside investor. Without being able to appropriate the marginal return of his monitoring effort fully, the old investor's monitoring incentives are blunted. This

5. For example, $\alpha = p_r = 0.5$, $I_1 = I_2 = 1$, $I_3 = 4$, and $R = 9$ satisfy Assumptions (i)–(iii).

6. If renegotiation were permitted at date 2 after the innovator learns the project type but before the capital I_2 is sunk, then there may exist a bribery scheme or a bad project detection mechanism such that the soft budget constraint may be avoided if $I_2 + I_3 - pR > B_H$ and $B_L > B_H$. This is because the bank would be better off by making a bribery offer of returning I_2 unused in exchange for a fee of $B_H + \varepsilon < I_2 + I_3 - pR$ to the innovator. An innovator with a high cost project would accept this deal, whereas an innovator with low cost type project would not (provided that $B_L > B_H + \varepsilon$). However, adding a very high cost type project is sufficient to rule out such a peculiar outcome, see Dewatripont and Maskin (1995), footnote 16 on p. 546).

will reduce the profitability of refinancing a high-cost project, and in turn reduce the outsider's incentives to refinance. Thus, decentralization with many investors credibly commit not to refinance high-cost projects at date 3. Knowing that, innovators with high-cost projects will stop at date 2 as soon as they learn the type of project they are stuck with. This corresponds to the notion of a "hard budget constraint." Although the above discussion regarding the contractual foundation of the soft/hard budget constraint is based on Dewatripont and Maskin (1995), our theory could be made entirely independent of their model, if one substitutes an alternative contractual foundation for the soft/hard budget constraint.

3. BUREAUCRATIC SCREENING AND FINANCIAL CONSTRAINTS

Why do centralized economies rely so heavily on bureaucracy in selecting projects even when bureaucracy is often blamed for damaging innovation? Our answer is related to the inability of the centralized economy to commit to hard financial constraints.[7] To see this, denote the expected net returns from one project without pre-screening in the centralized economy and the decentralized economy by π^c_{ns} and π^d_{ns} respectively, then

$$\pi^c_{ns} = \alpha(pR - I_1 - I_2) + (1-\alpha)(pR - I_1 - I_2 - I_3), \tag{1}$$

$$\pi^d_{ns} = \alpha(pR - I_1 - I_2) - (1-\alpha)I_1. \tag{2}$$

Similarly denote the expected returns from one project under the optimal decision rule with prescreening by π^c_{ps} and π^d_{ps}. Then we have (proofs of propositions are contained in the Appendix):

Proposition 1. *Expected returns under the optimal decision rule with pre-screening are given by*

$$\pi^c_{ps} = \delta\{[\alpha\gamma + (1-\alpha)(1-\gamma)](pR - I_1 - I_2) - (1-\alpha)(1-\gamma)I_3\}, \tag{3}$$

$$\pi^d_{ps} = \delta\{\alpha\gamma(pR - I_1 - I_2) - (1-\alpha)(1-\gamma)I_1\}. \tag{4}$$

Furthermore,

$$\pi^c_{ps} - \pi^c_{ns} > \pi^d_{ps} - \pi^d_{ns},$$

that is, the centralized economy uses more pre-screening than the decentralized economy.

According to Proposition 1, there are only three possibilities in our model: both economies use pre-screening; both economies do not use pre-screening; and only the centralized economy uses pre-screening (when $\pi^c_{ps} - \pi^c_{ns} > 0 > \pi^d_{ps} - \pi^d_{ns}$). In this sense, there is an "over-pre-screening" in the centralized economy as compared with the decentralized economy. The over bureaucratic prescreening in a centralized economy is optimal in order to avoid financing too many high-cost projects, which, once started, are hard to stop. Consequently, bureaucracy is an organizational response to the problem of the lack of commitment. In contrast, due to the hard budget constraint, investors in decentralized economies are able to terminate high cost projects *ex post* any way, thus reducing the benefits of pre-screening which is only based on the *prior* signal.

7. Our theory focuses on endogenizing bureaucracy by dealing with the problem of the soft budget constraint, which is caused by a centralized financial institution. In other models, bureaucracy could be a reason for soft budget constraints.

From Proposition 1 we also obtain:

Proposition 2. *Innovation in the centralized economy has the following features:*
(i) *because of the over-pre-screening, the centralized economy incurs more type I errors; and*
(ii) *projects are slower to complete in the centralized economy than in the decentralized economy due to the delays of both bureaucratic screening* ex ante *and refinancing of high cost projects* ex post.

In our model, the cost of bureaucratic pre-screening is two-fold. First, with imperfect information, pre-screening reduces type II errors (accepting high cost projects) at the expense of incurring type I errors (rejecting low cost projects). This effect exists even without costs of delay (i.e. when $\delta = 1$). Secondly, pre-screening delays all projects. Our model captures two different kinds of slowness in innovation in centralized economies. One comes from the presence of high cost projects which require slow refinancing. This is caused *directly* by the lack of commitment to terminate them by the creditor *ex post*. Another comes from the *ex ante* bureaucratic screening which delays all projects, including the low cost ones. This is associated with the search for and use of prior information and is caused *indirectly* by the lack of commitment in a centralized economy. The two kinds of slowness are related to the soft budget constraint of the centralized system.

Both kinds of delays in centralized economies are documented in the literature. Concerning the bureaucratic delays in approval of innovative projects, 40% of the 700 R&D projects proposed by the Siberian Division of the USSR Academy of Sciences between 1960 and 1970 had become obsolete while waiting for higher-level approval (Linz and Thornton (1988)); 25% of all construction projects in the Soviet 12th Five-Year Plan were designed 10 to 20 years ago. As examples, in 1985 the Ministry of Non-Ferrous Metallurgy approved 69 projects that were designed from 1965–1975, the Ministry of the Automotive Industry approved 20 projects proposed several years ago (Judy and Clough (1989)). About slowness of completion, Soviet economists estimate that development activities may take as much as 6 to 8 years in the Soviet Union, in contrast to 3–4 years in the U.S. (Linz and Thornton (1988)).

However, not all industries performed badly in centralized economies and some of them, such as aerospace, nuclear, and jet aircraft industries, were very good. Why is that the case? We need to examine the nature of different types of innovations. In our model, the nature of innovative projects is characterized by two sets of parameters: the uncertainty underlying the projects; and the investment requirements in different stages of innovation. We will analyze them in turn.

For innovative ideas based on sound scientific principles, technical uncertainty is relatively low. This means, other things being equal, that the level of prior knowledge (γ) and the probabilities of being low-cost or successful (α or p) are relatively large. But for innovative ideas developed from trial and error, technical uncertainties are usually very high, which means that γ, α, and p are relatively small.

Proposition 3. *Suppose* $\pi^d_{ps} > \pi^d_{ns}$ *at* $\gamma = 1$ *(that is, delay is not too costly), then*
(i) *there exist parameters* $\gamma^c < \gamma^d$, $\alpha^d < \alpha^c$ *and* $p^d < p^c$ *such that only the centralized economy uses pre-screening if and only if* $\gamma^c < \gamma < \gamma^d$, *or* $\alpha^d < \alpha < \alpha^c$, *or* $p^d < p < p^c$; *and*
(ii) *the efficiency gap between the two economies* ($\pi^d - \pi^c = \max\{\pi^c_{ns}, \pi^c_{ps}\} - \max\{\pi^d_{ns}, \pi^d_{ps}\}$) *increases as the prior knowledge* γ *becomes worse.*

Intuitively, when the prior knowledge is relatively good, both the centralized and decentralized economies use pre-screening because prior signals are very informative. Even in this case, deterioration of the prior knowledge will hurt more the centralized economy because the marginal value of the prior knowledge is higher in the centralized economy than in the decentralized economy. Similarly, when the quality of projects (i.e. probabilities of low-cost type and successful outcome) is relatively bad, both economies also use pre-screening. When prior knowledge deteriorates or the quality of projects improves, the decentralized economy first stops using pre-screening while the centralized economy continues to rely on bureaucratic screening. In this case, the deterioration of the signal hurts the centralized economy further but has no effect on the decentralized economy. Finally, when the prior knowledge is very poor or the quality of projects is very good, neither system uses pre-screening.

We now turn to investment requirements in different stages of innovation. Let $I_1 = \beta I$ and $I_2 = (1-\beta)I$. Then β is a measure of relative investment share at the research stage of innovation.

Proposition 4. *When β, I and I_3 satisfy Assumptions* (i)–(iii), *we have*

(i) *given I and I_3, there exists β^d such that only the centralized economy uses pre-screening if and only if $\beta < \beta^d$, and the efficiency gap between the two economies $(\pi^d - \pi^c)$ increases as β decreases; and*
(ii) *given I and β, there exists I_3^c such that only the centralized economy uses pre-screening if and only if $I_3 > I_3^c$, and the efficiency gap between the two economies $(\pi^d - \pi^c)$ increases as I_3 increases.*

For any given $I = I_1 + I_2$ and I_3, a decrease in β means that it is less costly for the innovators to obtain information about the cost type of the projects through research, moreover, savings from stopping high cost projects are higher. But the change of β has no effect in the centralized economy. Thus the decision on the use of pre-screening in the centralized economy is independent of β and a reduction in β increases the gap between the two economies. On the other hand, for any given β and I, an increase in I_3 increases the cost of a soft budget constraint, but it has no effect on the decentralized economy. Therefore, when I_3 increases, the centralized economy may start to use pre-screening, and the efficiency gap between the two systems also increases.

The above discussion is relevant to the study of comparative performance of decentralized economies vs. centralized economies with respect to different industries. First, the atomic-bomb technology and the computer technology are examples of good and poor prior knowledge respectively. In the case of atomic-bomb, related physics principles were well developed before engineering practices.[8] In contrast, the basic principles of computer science and solid state physics needed for making electronic components were only developed during or after the earlier generations of electronic computing machines were developed![9] Second, concerning the research stage investment requirements, jet fighter

8. The nuclear chain reaction was discovered and the related theory was developed in 1939. The experiment and the theory are sufficiently specific for guiding the development of an atomic bomb. The first atomic bomb was developed in the period of 1942-45 under the supervision of the physicists who developed the theory and chain reaction related experiments.

9. The first electronic computer was developed in the period of 1943-45. But the fundamental basic idea of the modern computing machine—the concept of the von Neumann machine—was developed in the period of 1944 45, thus the first electronic computer was not a modern computing machine in principle. Moreover, the transistor was invented in 1947 and the integrated circuit was invented in 1959.

projects, such as F-16 made by the U.S. and Mig-25 made by the former Soviet Union, require huge funding at the research stage. However, software projects are typically not very demanding for funding at the research stage.

According to Propositions 3 and 4, the difference in innovation in atomic-bomb and jet fighter projects between the centralized and the decentralized economies should not be significant, which is indeed the case. However, in the computer industry, evidence shows that the gap is huge and the centralized economy suffers more on mistakes and slowness. Due to its military importance, the computer industry has always been a high priority sector in both the Soviet Union and China. In the Soviet Union, research on electronic computers began in 1947, only four years after the U.S. The first Soviet computer was built in 1951, although six years behind the U.S., but six years ahead of Japan (China built its first electronic computer in the same year as Japan). However, the gap between the Soviet Union and the U.S. in the computer industry was already widened to fourteen years in 1965 (July and Clough (1988)). Even worse, the computer technology of the Soviet Union and the Eastern bloc in the late 1970s and the 1980s lagged behind many other decentralized economies such as Japan which also imitated the U.S. technology.

4. BUREAUCRACY AND PARALLEL RESEARCH

For any given technical problem, society as a whole only needs the best solution. But in order to obtain the best solution with a high probability, it is desirable for society to undertake several innovative projects simultaneously (i.e. "parallel research"). It is well expected that a central planner would select an optimal number of parallel projects to maximize the social value of innovation. However, we observe too few numbers of parallel projects in the centralized economy in many key high-tech industries. The question is, what prevents the bureaucracy from approving more parallel projects in those key industries, which is observed in decentralized economies and proved successful?

To address this question, we assume that the social value of a group of parallel projects is equal to the maximum value of each project (see Dasgupta and Stiglitz (1980), and Dasgupta and Maskin (1986)). For simplicity, suppose that there are two innovative projects which are stochastically independent. Then, the social value of the two projects is R if at least one of the two projects succeeds and zero otherwise. However, the private return to an investor is R if his project is the only one that is successful, $R/2$ if both projects are successful, and zero otherwise.

We will omit prior signal θ but maintain Assumptions (i) to (iii) in our basic model. Moreover, we assume that when a project is refinanced, the success or failure of the other project (even if low cost) is not yet known. We refer to the socially optimal number when high cost projects are screened out *ex post* as the socially optimal number of parallel research projects. Parallel research with two projects is socially optimal if and only if the expected *marginal* value of the second project is positive

$$\alpha p(1-\alpha p)R - I_1 - \alpha I_2 > 0. \tag{5}$$

In a centralized economy, bureaucracy takes charge of selecting projects for the economy, taking into account duplication costs. However, the soft budget constraints increase the expected cost of a project. Thus the expected cost of the second project is $I_1+I_2+(1-\alpha)I_3$. Given the probability of $p(1-p)$ that the first project fails and the second project succeeds, the expected marginal benefit of the second project is $p(1-p)R$ by the maximum criterion. In this case, two projects will be approved if and only if the expected *marginal* value of the second project is positive, that is

$$p(1-p)R-I_1-I_2-(1-\alpha)I_3>0. \quad (6)$$

However, Assumption (ii) implies that $\alpha p(1-\alpha p)R-I_1-\alpha I_2>p(1-p)R-I_1-I_2-(1-\alpha)I_3$. Thus, the number of projects started in a centralized economy is always smaller than or equal to the socially optimal number of parallel projects.

In a decentralized economy, two projects start when the expected *total* value of the two projects is positive because the expected return to each project is one half of the expected total return of the two projects. This condition is given by

$$(1-(1-\alpha p)^2)R-2I_1-2\alpha I_2>0, \quad (7)$$

which can be written as the sum of the marginal values of the two projects

$$[\alpha pR-I_1-\alpha I_2]+[\alpha p(1-\alpha p)R-I_1-\alpha I_2]. \quad (8)$$

Apparently there could be an over-duplication under decentralization when the marginal value of the second project (the second term) is negative but the total value of the two projects (the entire expression) is positive.

Proposition 5. *The number of projects started in a centralized economy is smaller than or equal to the optimal number of projects; the number of projects started in a decentralized economy is more than or equal to the optimal number of projects.*[10]

According to Proposition 5, the bureaucracy in the centralized economy may select a suboptimal smaller number of projects to start because of the soft budget constraints. While innovators in the decentralized economy tend to start too many projects because it is unable to internalize the externality from non-additive returns.[11] Indeed, the centralized economy always selects very few projects and mobilizes resources for these projects as special missions. But that is usually not the case in a decentralized economy.

However, the numbers and outcomes of parallel projects in the centralized economy vary in different industries as compared with decentralized economies. In some industries, such as the aerospace and nuclear technologies, not many projects are carried out in a decentralized economy either. But in electronics and computers, many projects are carried out in a decentralized economy. It is only in the latter case that the difference between the two systems appears to be significant. Given the importance of computers, what explains the "wrong" strategy of central planners? To address this question, we compare innovation in different technologies in the two systems.

Proposition 6. *There exist $p_1<p^*<p_2$ such that for any given mean return of a project $pR=r$, the centralized economy starts only one project but the decentralized economy starts two projects if and only if $p_1<p<p_2$; furthermore, two is optimal if $p<p^*$.*

When the probability of being successful is high, there is no difference between the two systems in determining the number of parallel projects. But when the probability is

10. If the number of projects in centralized and decentralized economies is the same, then the decentralized economy is more efficient. This is because if both economies start one project, the decentralized economy is more efficient due to the hard budget constraint. If both economies start two projects, the optimal number of projects is two (Proposition 5), thus the decentralized economy is again more efficient.

11. Aghion and Howitt (1992) discussed the possibility of sub-optimal numbers of innovative projects being undertaken in decentralized economies because of the threat of becoming obsolete due to later period competition.

relatively low, the lack of commitment forces the centralized system to choose a smaller number of projects.

Proposition 7. *Assume that the centralized economy starts only one project. Then,*

(i) *there exists β_1 such that for any given I, the decentralized economy starts two projects if and only if $\beta < \beta_1$; and*
(ii) *there exists $\beta^* < \beta_1$ such that two is optimal if $\beta < \beta^*$.*

When the share of research-stage investment in an innovative project is high, the number of parallel research projects in the two systems is the same. This is because the large research-stage investment will make the cost of starting more parallel projects too high even under a hard budget constraint. But when the research-stage investment is low, the centralized system starts fewer projects than the decentralized system. This is because once a project is started, it is too difficult to stop it later regardless of how low the research-stage investment is.

The above results illustrates the problematic patterns in innovation in the computer industry of the centralized economy. In the 1940s, when solid state physics was not mature enough to steer semiconductor projects into specific directions, several parallel research projects were carried out in the U.S. searching for the best technology. At that time, in contrast, the Soviet government rejected solid state technology proposals and concentrated all resources on a micro-tube technology project which was based on more mature electronics principles. This turned out to be a big mistake. To catch up with Western countries, in 1965, the Soviet government decided to mobilize huge amounts of resources and to collaborate with other Eastern bloc countries to imitate the U.S. computer technology (i.e. IBM technology). Since then, the Soviet government has organized and financed the giant RIAD (unified series) project to develop mainframe computers. Eastern bloc countries, monopolized by RIAD, have concentrated only on this project to develop IBM compatible mainframe computers for more than two decades. During the same period, however, there were dozens of projects competing with one another in decentralized economies. The difference in the number of parallel research projects is striking, and the Soviet computer industry failed, which is one of the main reasons that the Soviet Union was unable to compete with "Star Wars."

5. CONCLUDING REMARKS: INNOVATIONS OF LARGE VS. SMALL FIRMS IN DECENTRALIZED ECONOMIES

Although our primary comparison in the paper is between centralized and decentralized economies, much of our analysis are also relevant in comparing innovative practices of alternative institutions within decentralized economies, as their degrees of softness of budget constraints vary. First, our theory is relevant to government funded *vis-a-vis* privately funded innovative projects in decentralized economies. The British–French government funded Concorde project shows similar features of inefficiency in a centralized economy, such as slowness in revealing the true cost of the project and "unlimited funding" to refinance the project after the revelation of bad news. The result was a technical success but an economic disaster (Feldman (1985)).

Second, our theory also has implications concerning the roles of large vs. small firms in innovation in decentralized economies, since small firms, such as venture capital firms, usually have harder budget constraints than large corporations.[12] The management literature reports the following stylized facts which are consistent with predictions of our theory. (A) Large corporations tend to use more bureaucracies (e.g. committees of executives) to approve innovative projects (Stinchcombe (1990)). (B) Large corporations tend to choose safer innovative projects. Systematic studies of R&D practices in the U.S. show that large companies devote more attention to perfection-related or cost-reduction-related innovation and less to new-product-related innovation (Scherer (1991), (1992)). Corporate executives tend to restrict their R&D activities in less uncertain and less novel projects (Jewkes *et al.* (1969), Nelson *et al.* (1967)). (C) Large corporations tend to avoid projects requiring smaller research funding, and the financial appraisal standards applied to innovative projects requiring small research funding were often significantly higher than those applied to projects requiring large research funding (Lonie *et al.* (1993)).[13] Consistently, "idea-rich small firms originate a disproportionate share of innovations" (Scherer (1992)).[14]

Finally, our analysis is also relevant in comparing different decentralized economies, such as comparing large Japanese firms and small American venture capital firms. The Japanese firms devote more resources to engineering-perfection (safer) types of innovations with outstanding performance (Mansfield (1988)); are not successful in making break-through (high-risk) types of innovations (Aoki (1990)). Recently, Japanese corporations failed in their government-coordinated large-scale projects aimed at making break-throughs in high-definition televisions and fifth generation computers. Also, large Japanese corporations more often buy innovative products from, or form joint ventures with, small American venture capital firms.

APPENDIX

Proof of Proposition 1. It is standard to show that the optimal decision rule for the investor is either no pre-screening with all projects being approved, or approve if $\theta=\theta^L$ and reject if $\theta=\theta^H$. Using equations (1)-(4), we have $(\pi^c_{ps}-\pi^c_{ns})-(\pi^d_{ps}-\pi^d_{ns})=-(1-\delta(1-\gamma))(1-\alpha)(pR-I_2-I_3)$. By Assumption (ii), $pR-I_2-I_3<0$. Together with $\delta(1-\gamma)<1$, we obtain $\pi^c_{ps}-\pi^c_{ns}>\pi^d_{ps}-\pi^d_{ns}$.

Proof of Proposition 3. Define γ^c and γ^d such that $\pi^c_{ns}=\pi^c_{ps}(\gamma^c)$ and $\pi^d_{ns}=\pi^d_{ps}(\gamma^d)$. Since π^c_{ps} is an increasing linear function of γ, we have $\pi^c_{ps}\leqq\pi^c_{ns}$ if and only if $\gamma\leqq\gamma^c$. Similarly for π^d_{ps}. It is then easy to show $\gamma^c<\gamma^d$, and when $\gamma>\gamma^d$, pre-screening is used in both systems; when $\gamma^c<\gamma<\gamma^d$, pre-screening is only used in the centralized economy; and when $\gamma<\gamma^c$, pre-screening is used in neither economy. A similar proof applies to the cases of α and p. ||

Proof of Proposition 4. (i) Given I and I_3, π^c_{ns} and π^c_{ps} are independent of β. Because $d\pi^d_{ns}/d\beta=-(1-\alpha)I<d\pi^d_{ps}/d\beta=-\delta(1-\alpha)(1-\gamma)I$, there exists β^d such that $\pi^d_{ns}>\pi^d_{ps}$ if and only if $\beta<\beta^d$. Also $d(\pi^d-\pi^c)/d\beta=-d\pi^d/d\beta<0$. Then use Proposition 1. (ii) A similar proof applies. ||

Proof of Proposition 5. Because (5) implies (7), the number of projects started in a decentralized economy cannot be less than the optimal number. Using Assumption (ii), we show that $\alpha p(1-\alpha p)R-I_1-\alpha I_2<0$ implies $p(1-p)R-I_1-I_2-(1-\alpha)I_3<0$. Hence if the marginal benefit of the second project is negative under decentralization, it is also true under centralization. ||

12. Large corporations have a tendency to maintain the stability of their R&D organization. In particular, R&D budgeting in large corporations is usually not based on individual projects, which implies revenue smoothing across projects (Mansfield (1968), p. 62, and Reeves (1958)).

13. The "hurdle rates" applied to projects requiring small research funding were found to be four times as high as those applied to large investment projects in twelve large U.S. manufacturing companies (Ross (1986)).

14. A majority of the 100 most important innovations during the period 1900–1950 was invented by small firms (Jewkes *et al.* (1969)). Recently, 18 of 21 types of software originated with start-up firms, although the best-selling versions were marketed by established large firms (Prusa and Schmitz (1991)).

Proof of Proposition 6. Fix $pR = r$, and defining p_1, p^*, and p_2 as zeros in equations (6), (5) and (8) respectively. Then the proof follows. ||

Proof of Proposition 7. Fix $I_1 + I_2 = I$, and define β_1 and β^* as zeros in equations (8) and (5) respectively. Then the proof follows. ||

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