"ENVIRONMENTAL REGULATION AND INNOVATION"

by

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ENVIRONMENTAL REGULATION AND INNOVATION

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ABSTRACT

The paper considers a case where the threat of environmental regulation can be used by a government to induce a domestic firm to engage in a socially desirable product-development effort. We use a stochastic game to show that even if the government is restricted to Markov strategies, a non-trivial, self-enforcing incentive scheme can be devised. More efficient outcomes can be implemented by equilibria using strategies that condition on the payoff-irrelevant history. We give an example of such an equilibrium.

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[1] We wish to thank Rafael Rob for a useful conversation.

1. Introduction

Corrective policies for environmental externalities may take a number of forms, such as emission taxes, emission-abatement subsidies, direct regulation through technical standards - individual or aggregate - or tradeable permits (see Baumol and Oates, 1988)[2]. Each of these instruments raises specific problems, but some issues are common to all. First, a government attempting to enforce socially desirable norms on private firms is likely to face familiar information-elicitation problems (see Laffont and Tirole, 1992, and references therein). For instance, when firms have private information on the cost of compliance to new regulation and regulators cannot precommit to a future course of action, a well-known *ratcheting effect* appears[3] (see e.g. Weitzman (1980); Freixas, Guesnerie and Tirole (1985), and Rey and Salanié (1990)). Ratcheting has been studied in the context of environmental regulation by Yao (1989). Second, environmental regulation affects technology choices, and the question of whether tighter standards can be held responsible for reduced productivity growth has attracted a considerable amount of attention, particularly in the United States. Finally, independently of the

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[2] An alternative route, in the tradition of Coase (1960) is the definition of property rights.

[3] Ratcheting refers to a situation that is well-known to prisoners of war. If they work hard initially, they elicit information on their working capabilities which may be used by the camp authorities to increase their future workload. In the absence of precommitment, the equilibrium outcome thus involves suboptimal effort in the first period.

information structure, government enforcement of social objectives in the absence of precommitment raises time-consistency issues (Malik, (1991)). Such issues matter in particular for the effect of environmental regulation on incentives for innovation (see Downing and White (1986) and Milliman and Prince (1989) for a comparison of different policy instruments).

In this regard specific problems arise in a small open economy, where industrial-policy concerns may clash with environmental objectives (see Carraro and Siniscalco (1991)). In a country taking a leading position in setting new environmental standards, the standard-setting process is likely to involve extensive bargaining between producers and government agencies (Spulber (1989); trade issues are considered separately by Krutilla (1991); see also the recent survey by Dean (1991)). By contrast, in a "follower" country, foreign standards, especially if they come from a large country, constitute an exogenous reference. Environmental-policy problems are then related to more general standard-harmonization problems (Dean (1991)) and adopting foreign standards can be viewed, to some extent, as a process of trade liberalization[4]. Time-consistency issues such as those considered

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[4] The usual argument is that tighter national standards can be used as non-tariff barriers. However slack standards can also be used as an instument of industrial policy. Automobile catalytic converters, for instance, add a fixed cost to each vehicle, thus distorting demand in favor of relatively more expensive cars. This penalizes "generalist" producers such as Renault and PSA of France, to the benefit of upscale "specialist" producers such as BMW or Mercedes. Delaying adoption of the converter on the domestic French market is then an obvious industrial-policy ploy, especially if an alternative technology with different cost characteristics, such as the "lean-burn" engine, can be developed.

by Matsuyama (1990) are thus likely to arise. What makes the problem of environmental regulation distinct and interesting, however, is that it combines these issues with issues of incentives for innovation.

We consider the problem of a government facing pressure to adopt stricter pollutant emission standards while a domestic producer may potentially develop a new technology to meet those standards. A foreign technology already exists, so that if the government adopts the new standard now, the home firm must buy the foreign technology. On the other hand, if the government waits, it is possible that the home firm will develop its own technology, in which it will be a leader. It is assumed that the social return to the home technology development effort is positive, while its private return is negative, so that the government needs an incentive scheme to induce the firm to start the development process. Furthermore, the government would, of course, like to see the firm's development effort bear fruit, which may require some time. The government's problem is then to trade off this argument against the cost of waiting before enacting the regulation. As the government's incentive scheme hinges on its option to regulate at once, this option must constitute a credible threat. We show that a simple, time-consistent incentive scheme can be implemented by a Markov perfect equilibrium. Such a scheme imposes minimal information requirements, as the government needs only to know in each period where the development process currently stands, irrespective of the firm's actual effort. This "primary" scheme can then be used to implement a more efficient one as a perfect equilibrium. The latter uses history-dependent strategies, so it imposes heavier information requirements.

The paper is organized as follows. Section 2 presents the model. The main results are stated and discussed in section 3. Section 4 concludes.

2. The Model

2.1 Timing and stochastic structure

The game in extensive form is depicted in figure 1. The players are the government (G) and a domestic firm (F). At the beginning of each period t, the government chooses to enact (r) or to delay ($\bar{r}$) stricter standards concerning the emission of pollutants. If the former decision is taken, the game ends. If the government chooses not to regulate now, the firm may decide to pursue (d) or not to pursue ($\bar{d}$) the development of its own cleaner technology[5]. Success in developing the home technology is uncertain. Furthermore, reducing emissions to the level compatible with the new standards takes two stages[6]: the firm must first go

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[5] The assumption of fixed intensity of R&D effort is also used by Fudenberg, Gilbert, Stiglitz and Tirole (1983) and by Choi (1991).

[6] Stochastic models of innovation with multi-stage development processes have been studied by Grossman and Shapiro (1987) and Harris and Vickers (1987) among others. Both papers study R&D races between two firms and allow for variable R&D intensities. We consider here the simple case where there is only one home firm capable of developing the alternative technology, as in Grossman and Shapiro (1986).

from an initial state of high emissions (e_h) through a medium yet unsatisfactory level (e_m) before reaching the low, appropriate level (e_ℓ). The probabilities p_{jk} governing transition of the emission process $\{e_t\}$ from a state e_j to a state e_k, constitute the following Markov matrix:

$$\begin{bmatrix} p_{hh} & p_{hm} & 0 \\ 0 & p_{mm} & p_{m\ell} \\ 0 & 0 & 1 \end{bmatrix}$$

When the "dummy" state e_ℓ is reached, the government enacts the new standard and the game ends. Until this happens, play is repeated given the actual state of the home technology.

2.2 Payoffs

Until the firm has reached state e_ℓ and unless the government has introduced the new regulation, the firm and the government receive instantaneous payoffs normalized to zero[7]. The firm incurs a flow cost of c in each period where it decides to pursue the development of the cleaner technology, and discounts future earnings by a factor $0 < \delta_F < 1$.

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[7] This normalization of payoffs does not imply that actual profits are zero. We assume that the firm's market power ensures that it earns, initially, a monopolistic rent. This rent corresponds to the "zero" payoff under the status quo. Negative payoffs mean reductions of the firm's rent. We assume that the worst outcome still entails some positive profits, so that exit does not take place. For a detailed treatment of the exit issue, see Carraro and Siniscalco (1991).

If the government regulates before the home technology development is completed, the government and the firm receive respectively v_r^G, v_r^F per period, from the *current* period onwards. If state e_ℓ is achieved, the government and the firm receive respective payoffs v_ℓ^G and v_ℓ^F from the *next* period onwards. The government also discounts the future by a factor $0 < \delta_G < 1$.

The firm's and government's preferences over payoffs are represented by the following inequalities:

$$\begin{aligned} v_r^F &< 0 < v_\ell^F \\ 0 &< v_r^G < v_\ell^G \end{aligned} \tag{1}$$

The firm's first inequality means that early regulation, before the home technology is developed, is the worst of all outcomes; the second inequality means that an outcome where new standards are imposed when the firm has succeeded is best and is in particular better than the status quo, for it gives the home firm a leadership position in the new technology. The government's first inequality implies that forcing regulation on the unprepared firm is better than the status quo; the second inequality says that the government internalizes the firm's objectives to some extent, by putting a premium on having the firm prepared.

2.3 Strategy space

In general, a strategy for the firm (the government) is a sequence $\{s_t^F\}$ ($\{s_t^G\}$) of functions $s^F\colon H_t \to [0,1]$ ($s^G\colon H_t \to [0,1]$)

mapping game histories up to time t into probabilities of developing the cleaner technology (of enacting stricter emission standards). Histories include the current state e_t, which in fact entirely describes the actual "state of the game".

In this notation a Markov strategy for player i, $i = F,G$, is a function $s^i\colon E \rightarrow [0,1]$ defined on the state space $E = \{ e_h, e_m, e_\ell \}$. That is, such strategies condition only on the current state e_t of the development process and specify identical moves for periods where the process is in the same state.[8] Actions prescribed in each particular state by a Markov strategy will then be denoted as s_j^i, $j = h, m, \ell$.

3. Solution and main result

Markov strategies appear plausible in the present context, because failure does not carry any information on the chances of success.[9] Within this class of strategies, one can find sufficient conditions on the game parameters so that, in a perfect equilibrium, as the emission level of the domestic technology improves, the government delays regulation and the firm consistently pursues the development effort. This is formally

[8] See Maskin and Tirole (1989) and Fudenberg and Tirole (1991) for formal definitions, examples, and references.

[9] If the parameters of the development process were to be learnt over time, as in a "bandit" problem, restricting the strategy space to Markov strategies would be more problematic.

stated in the following proposition.

Proposition 1. *If*

$$\left[\frac{\delta_F}{1-\delta_F}\right] p_{ml} v_l^F > c \tag{2}$$

$$\delta_G \left(p_{ml} v_l^G + p_{mm} v_r^G\right) > v_r^G \tag{3}$$

$$\frac{v_r^F}{1-\delta_F} < \frac{v_l^F}{1-\delta_F} - \frac{2c}{\delta_F\, p_{hm}} < \delta_F \frac{v_r^F}{1-\delta_F} \tag{4}$$

$$(1-\delta_G p_{hh})\,(1-\delta_G p_{mm})\, v_r^G < \delta_G^2 p_{hm} p_{ml} v_l^G \tag{5}$$

there exists a Markov perfect equilibrium such that

$0 < s_h^G < 1$, $0 < s_h^F < 1$; and $s_m^G = 0$, $s_m^F = 1$.

Proof

We solve the game backward, using dynamic programming. Let V_m^F, V_m^G denote the continuation payoffs of the firm and the government for playing the above strategies when the domestic technology is in state m. A firm who plays $s_m^F = 1$ gets

$$V_m^F = \frac{-c+\delta_F \dfrac{v_l^F}{1-\delta_F}}{1-\delta_F(1-p_{ml})} \tag{6}$$

On the other hand, playing $s_m^F = 0$ yields $\delta_F V_m^F$. Clearly, the firm sticks to playing $s_m^F = 1$ provided that condition (2) holds. The government opting for $s_m^G = 1$ gets $v_r^G/(1-\delta_G)$, while choosing $s_m^G =$ 0 brings

$$V_m^G = \delta_G [p_{m\ell} \frac{V_\ell^G}{1-\delta_G} + (1-p_{m\ell})\, V_m^G] \tag{7}$$

Condition (3) ensures that the latter is a better move.

Now, let $V_h^F(s_h^G)$ (respectively $V_h^G(s_h^F)$) denote the continuation payoff of the firm (the government) for playing the above strategies when the state is e_h and the government (the firm) plays s_h^G (s_h^F). If the strategies described in the proposition exist, we have that

$$\begin{aligned}\delta_F (s_h^G \frac{V_r^F}{1-\delta_F} + (1-s_h^G)\, V_h^F(s_h^G)) &= \\ -c + \delta_F [(1-p_{hm})\, (s_h^G \frac{V_r^F}{1-\delta_F} &+ (1-s_h^G)\, V_h^F(s_h^G)) + p_{hm} V_m^F]\end{aligned} \tag{8}$$

$$\frac{V_r^G}{1-\delta_G} = \delta_G [(1-s_h^F)\, V_h^G(s_h^F) + s_h^F (1-p_{hm})\, V_h^G(s_h^F) + p_{hm} V_m^G)] \tag{9}$$

i.e., the firm and the government are made indifferent between d and $\bar{d}$ and r and $\bar{r}$, respectively. Clearly, as the payoff to a given player does not depend here on what he or she does, but rather on what the *other* player does, neither is tempted to deviate from such strategies. Let us then prove their existence. By the last equations,

$$s_h^G = \frac{-c + \delta_F p_{hm} [V_m^F - V_h^F(s_h^G)]}{\delta_F p_{hm} \; [\frac{V_r^F}{1-\delta_F} - V_h^F(s_h^G)]} \tag{10}$$

$$s_h^F = \frac{\dfrac{V_I^G}{\delta_G(1-\delta_G)} - V_h^G(s_h^F)}{p_{hm}[V_m^G - V_h^G(s_h^F)]} \tag{11}$$

Conditions (4) and (5) ensure that the above right-hand-side functions of s_h^G, s_h^F are strictly between 0 and 1. The validity of the equations (10) and (11), and therefore the existence of equilibrium mixed strategies, can then be established via a simple fixed-point argument. *Q.E.D.*

Conditions (2) to (5) together define a region in the parameter space $(\delta_F, \delta_G, v_r^F, v_r^G, v_t^F, v_t^G)$ where the profile described in the proposition is a Markov perfect equilibrium. For future discussion, we will call this equilibrum profile σ_1.

Condition (2) ensures that the firm plays *d* in state m. It is a cost-benefit inequality, as $[\delta_F/(1-\delta_F)]p_{mt}v_t^F$ is an expected discounted benefit from action (it appears as a payoff because the status-quo payoff is normalized to zero). Obviously, it places an upper bound on the development cost c or a lower bound on terminal payoff v_t^F , which the firm obtains upon successful development of the home technology. Condition (3) ensures that the government is willing to play $\bar{r}$ in state m. It might be called a "carrot-stick" calculation: the carrot is the government's pledge to refrain from regulating in state m, while the stick is the immediate regulation option. The incentive scheme hinges on the government's ability to commit to the no-regulation pledge in state m, which is ensured by condition (3)[10]. It implies that the expected benefit from waiting one more period in state m is always greater than the benefit from regulating at once.

Condition (4) ensures that the government is willing to randomize in state h. It comprises two simple inequalities. The first one,

$$\left[\frac{\delta_F}{1-\delta_F}\right] p_{hm}\,(v_l^F - \delta_F v_r^F) < 2c \quad , \qquad \textbf{(12)}$$

means that in state e_h the firm would not be willing *ex ante* to enter the development of the cleaner technology. Hence, $s_h^G > 0$ is necessary to get the firm to act. The second inequality,

$$\left[\frac{\delta_F}{1-\delta_F}\right] p_{hm}\,(v_l^F - v_r^F) > 2c \quad , \qquad \textbf{(13)}$$

suggests that the firm has regret *ex post* for not having the opportunity to act if the government regulates. Hence, $s_h^G < 1$ is enough to get the firm to act. As usual, randomization for one player is induced by what the other player is doing. Finally, condition (5) ensures that the firm is willing to randomize in state h. It is again a cost-benefit comparison using two-step

[10] The reader may wonder how incentives can ever appear in a Markov equilibrium. The answer is that by randomizing in state h but not in state m, the government creates a benefit for the firm from trying to get out of state h and into state m, where it is insured against surprise regulation. In doing this, the government effectively alters incentives without conditioning on the payoff-irrelevant history. Once state m is attained, the private return to the development project becomes positive. This reflect the familiar result that the value of an R&D program increases with the number of stages completed (see Grossman and Shapiro (1986, 1987)).

transition probabilities.

In order to obtain efficiency results, we now define the "government's best".

Proposition 2

Let $\sigma = (s^F, s^G)$, where $s^F = (s_h^F, s_m^F)$ and similarly for s^G. Under conditions (2) to (5), the government's payoff is maximized by $\sigma^* = [(1,1);(0,0)]$.

Proof

Through tedious but straightforward algebra, it can be established that in $[0,1]^4$,

$$\begin{aligned} \frac{\partial V_h^G}{\partial s_j^G} &< 0 \qquad \text{for} \quad j = h,m \\ \frac{\partial V_h^G}{\partial s_j^F} &> 0 \qquad \text{for} \quad j = h,m \end{aligned} \tag{14}$$

so that $s_j^{F*} = 1$ and $s_j^{G*} = 0$ for all j. *Q.E.D.*

Proposition 3

Under conditions (2) to (5), σ^* is not a Markov equilibrium strategy profile.

Proof

It has already been established in the proof of proposition 1 that if $s_m^F = 1$ and $s_m^G = 0$, $s_h^F = 1$ and $s_h^G = 0$ are not mutual best responses. *Q.E.D.*

We have established that the Markov equilibrium profile of proposition 1, while self-enforcing, does not satisfy the government. Can we do better and find a self-enforcing profile that implements the shortest path to v_f? The answer is yes, once the Markov restriction is lifted. The trick is familiar: strategies that condition on the payoff-irrelevant history can be constructed that enforce an outcome on the frontier by imposing punishments on deviators. Here, the problem is to induce the firm to act always.

Consider the following partition of the set of histories H_t: $P_t^r = \{R_t, \bar{R}_t\}$, where $R_t = \{h_t : \exists\ \tau \leq t\ s.t.\ s_\tau^G = r\}$. P_t^r partitions H_t into the set of histories where regulation has already taken place (R_t), and its complement. Similarly, let $P_t^d = \{D_{tj}, \bar{D}_{tj}\}$ partitions H_t into the set of those histories where the firm did nothing in the current state in some previous period $(\bar{D}_{tj})$, and the complement of that set. Formally, $\bar{D}_{tj} = \{h_t : e_t = e_j \text{ and } \exists\ \tau \leq t\ s.t.\ e_\tau = e_j \text{ and } s_\tau^F = \bar{a}\}$.

Proposition 4

Let $\sigma_2 = [\{s_t^F\}, \{s_t^G\}]$ be the following profile:

$$s_t^F = \begin{cases} 0 & \text{on } R_{tj} \;\; \forall j \\ s_h^F & \text{on } \bar{D}_{th} \\ 1 & \text{on } D_{th} \end{cases} \qquad\qquad (15)$$

$$s_t^G = \begin{cases} s_h^G & \text{on } \bar{D}_{th} \\ 0 & \text{elsewhere} \end{cases}$$

Under conditions (2) to (5), σ_2 is a subgame-perfect equilibrium profile for the game.

Proof

For any j, let $\Gamma(\bar{R}_{tj})$ designate any subgame reached after a history in $\bar{R}_{tj}$. On $\Gamma(\bar{R}_{tm})$, σ_2 is identical to σ_1, the profile defined in proposition 1. On Γ_{th}, we have to establish that the firm does not want to deviate. Let $V_j^F(\sigma_2)$ be the firm's continuation payoff on the equilibrium path of σ_2 when the current state is j.

$$V_h^F(\sigma_2) = \frac{-c + \delta_F p_{hm} V_m^F(\sigma_2)}{1 - \delta_F p_{hh}} \qquad (16)$$

where

$$V_m^F(\sigma_2) = \frac{-c + \left(\dfrac{\delta_F}{1-\delta_F}\right) p_{m\ell} v_\ell^F}{1 - \delta_F p_{mm}} \qquad (17)$$

Similarly, let $V_h^F(\sigma_1)$ be the firm's continuation payoff along σ_1 when the state is h. After some algebra, and using s_h^i $(i = G,H)$ to denote the moves of the firm and the government in σ_1 defined respectively by (10) and (11), we have

$$V_h^F(\sigma_1) = \frac{-cs_h^F + \dfrac{\delta_F}{1-\delta_F} s_h^G (1-p_{hm}s_h^F)\, v_r^F + \delta_F s_h^F p_{hm} V_m^F(\sigma_1)}{1-\delta_F(1-s_h^G)\,(1-p_{hm}s_h^F)} \tag{18}$$

where $V_m^F(\sigma_1) = V_m^F(\sigma_2)$. The firm's incentive constraint is that the continuation payoff on the equilibrium path be at least as large as the continuation payoff from a deviation, *i.e.* $V_h^F(\sigma_2) \geq V_h^F(\bar{d})$, where $V_h^F(\bar{d}) = (\delta_F/1-\delta_F)s_h^G v_r + \delta_F(1-s_h^G)V_h^F(\sigma_1)$. As usual, this depends on δ_F. For $\delta_F = 0$, $V_h^F(\bar{d}) = 0 > -c = V_h^F(\sigma_2)$, so the condition is violated and the equilibrium is not sustainable. As $\delta_F \to 1$, we can compute

$$\begin{aligned} \lim_{\delta_F \to 1} \frac{V_h^F(\sigma_2)}{V_h^F(\bar{d})} &= \lim_{\delta_F \to 1} \frac{(1-\delta_F)\, V_h^F(\sigma_2)}{(1-\delta_F)\, V_h^F(\bar{d})} \\ &= \frac{v_t^F}{av_r^F + bv_t^F} \end{aligned} \tag{19}$$

where

$$\begin{aligned} a &= \frac{s_h^G}{1 - (1-s_h^G)\,(1-p_{hm}s_h^F)} \\ b &= \frac{p_{hm}s_h^F\,(1-s_h^G)}{1 - (1-s_h^G)\,(1-p_{hm}s_h^G)} \end{aligned} \tag{20}$$

The firm's incentive condition can be rewritten as $[(1-b)/a] > v_r^F/v_t^F$, and a sufficient condition is $b < 1$ (since $v_r^F < 0 < v_t^F$, and a can be easily seen to be positive). But a look at (20) shows that this is true. By continuity of $V_h^F(\sigma_2)$ and of $V_h^F(\bar{d})$ in δ_F, there is thus a critical $\delta_F^* \in (0,1)$ such that whenever $\delta_F \geq \delta_F^*$, σ_2 is an equilibrium profile. Finally, using the partitions P_t^d and P_t^r, let

$\Gamma(\bar{D}_{tj} \cap \bar{R}_{tj})$ designate any subgame reached after a history in $\bar{D}_{tj} \cap \bar{R}_{tj}$. The continuation profile of σ_2 in $\Gamma(\bar{D}_{tj} \cap \bar{R}_{tj})$ becomes identical with that of σ_1; hence, σ_2 is subgame-perfect.

Q.E.D.

Proposition 4 identifies a subgame-perfect equilibrium that uses the incentive scheme described in proposition 1 only as a threat, so that, provided that the conditions for its feasibility are met, it implements the government's preferred solution and avoids the inefficiency associated with the Markov equilibrium. Of course, the increased sophistication of the strategies requires a greater degree of understanding between the firm and the government. The equilibrium is therefore less robust to misunderstandings. On the other hand, given the irreversibility of the government's threat, it is important that we can pinpoint an equilibrium where it does not have to activate it.

4. Conclusion

Our results hold in a region of the parameters defined by conditions (2) to (5). Other regions can be identified, with different incentive problems. When the development cost c is sufficiently high and the government's threat to the firm v_r^F is low enough in absolute value, an equilibrium can be found where the firm never engages in development. Conversely, when the development cost c is low enough, the incentive problem becomes trivial as the firm engages in development even in the absence of government incentives.

The outcome implemented by proposition 1 describes a situation where the government uses the threat of enforcement of the foreign standard to induce the firm to act (in a probabilistic sense). The cost of implementing the solution in a time-consistent way is shared by the firm and the government. The firm engages probabilistically in a development effort that has a negative private return, while the government engages, also probabilistically, in a costly unanticipated regulation. What drives the incentive scheme is the government's promise that, once the development process has reached an intermediate stage, it will refrain from unanticipated regulation. This gives the firm an incentive to try to reach that stage, after which the private return to the project becomes positive.

As a practical illustration, one may think of the fight over EC automobile emissions standards (see Gabel, 1991). Our result suggests how the threat of immediate enforcement of German-style standards might have been used by the French and UK governments to induce effort in the development of the so-called lean-burn engine - PSA and Ford's alternative technology. What is interesting is that the scheme described in proposition 1 does not require any information on the firm's actual effort, nor on the time required for completion, but only on progress so far, which is easier to assess.

The two-stage structure of profile σ_1 is also a noteworthy feature. In the initial stage, both government and firm randomize, so that the degree of commitment is low. After one success, the firm raises its degree of commitment by switching to a "pure" action rule. Simultaneously, the government now commits, tacitly of course, not to regulate before the firm makes the breakthrough to the last stage. Both stick to their committed rule of action for as long as it takes to make the final breakthrough[11]. In variable-intensity models, the intensity of effort increases with the number of stages completed. The switch from mixed to pure actions along the firm's equilibrium strategy reflects the same mechanism, namely the increase in the value of the firm's program with the number of stages completed. This feature, which reappears in the equilibrium of proposition 2 as the disappearance of punishment for deviations, is reminiscent of the notion of "escalating commitment", familiar to students of organizational behaviour.

[11] Note that this may take a while, and the firm may end up throwing arbitrarily large amounts of money in the development process, as past expenditure is always considered as sunk and therefore irrelevant for current decisions.

References

W. Baumol and W. Oates, *The Theory of Environmental Policy*, Cambridge U. press (1991).

C. Carraro and D. Siniscalco, "Environmental innovation policy and international competition", CEPR discussion paper 525 (1991).

J. P. Choi, "Dynamic R&D competition under 'hazard rate' uncertainty", *Rand Journal of Economics* 22, 596-610 (1991).

R. H. Coase, "The problem of social cost", *Journal of Law and Economics* 3, 1-44 (1960).

J. Dean, "Trade and the Environment: a survey of the literature", mimeo, Johns Hopkins (1991).

P. B. Downing and L. J. White, "Innovation in pollution control", *Journal Econ. Management* 13, 18-29 (1986).

X. Freixas, R. Guesnerie, and J. Tirole, "Planning under incomplete information and the ratchet effect", *Review of Economic Studies* 52, 173-191 (1985).

D. Fudenberg, R. Gilbert, J. Stiglitz, J. Tirole, "Preemption, leapfrogging and competition in patent races", *European Economic Review* 22, 3-31 (1983).

D. Fudenberg and J. Tirole, *Game Theory*, The MIT Press, Cambridge, MA (1991).

H. L. Gabel, "European exhaust emission standards for small cars", INSEAD case (1991).

G. Grossman and C. Shapiro, "Optimal dynamic R&D programs", *Rand Journal of Economics* 17, 581-593 (1986).

____ and ___, "Dynamic R&D competition", *Economic Journal* 97, 372-387 (1987).

C. Harris and J. Vickers, "Racing with uncertainty", *Review of Economic Studies* 54, 1-21 (1987).

K. Krutilla, "Environmental regulation in an open economy"; *J. Environ. Econ. Management* 20, 127-142 (1991).

J.-J. Laffont and J. Tirole, "Should Governments commit?" *European Econ. Review* 36, 345-354 (1992).

A. S. Malik, "Permanent versus interim regulations: a game-theoretic analysis", *J. Environ. Econom. Management* **21**, 127-139 (1991).

E. Maskin and J. Tirole, "Markov equilibrium", mimeo, Harvard (1991).

K. Matsuyama, "Perfect equilibrium in a trade liberalization game"; *American Economic Review* 80, 480-492 (1990).

S. R. Milliman and R. Prince, "Firm incentives to promote technological change in pollution control", *Journal Environ. Econ. Management* 17, 247-265 (1989).

P. Rey and R. Salanié, "Long-term, short-term, and renegotiation: on the value of commitment in contracting", *Econometrica* 58, 597-620 (1990).

D. Spulber, *Regulation and markets*, MIT press (1989).

M. L. Weitzman, "The ratchet principle and performance incentives", *Bell Journal of Economics* 11, 302-308 (1980).

D. A. Yao, "Strategic responses to automobile emissions control:A game theoretic analysis", *J. Environ. Econom. Management* **15**, 419-438 (1988).

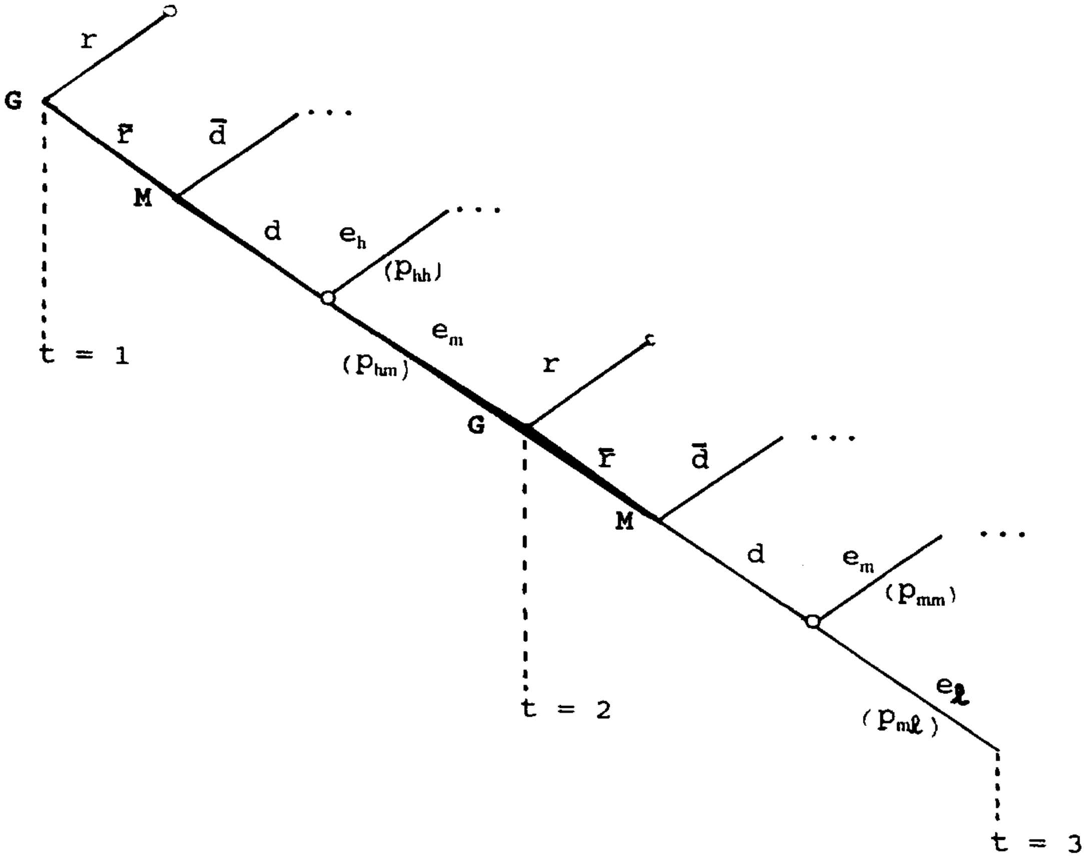

Fig. 1. The regulation game