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Inspection games with long-run inspectors

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Abstract

A single, long-run policeman faces a large population of myopic would-be criminals. This paper shows that this interaction has counterintuitive comparative static properties. A forward-looking inspector might tolerate more law violations than a short-sighted one.

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1 Introduction

Game theoretical models of law-enforcement (Graetz e.a. [12], Tsebelis [16] [17], Holler [11], Franckx [6], Saha and Poole [14], Cressmann e.a. [5], Andreozzi [1]) show a puzzling analogy with the predator-prey relationships studied in theoretical ecology: they have conterintuitive comparative static properties and generate oscillations. Let start with comparative statics. Killing predators will not reduce the number of predators, but will only increase the number of their preys. Similarly, killing preys will only reduce the number of predators. In the law enforcement literature a mathematically analogous result holds true. Increasing penalties will not reduce crime, but will only reduce the frequency of police inspections. In general, the only way to change the behavior of would-be criminals is to modify the policemen's payoffs and *vice versa*. This result has been taken as a proof that the standard economic approach to crime deterrence inspired to Gary Beker's [3] seminal paper (that neglects strategic considerations) might be flawed. (Tsebelis [16], Holler [11].)

Oscillations are due to the hypothesis that police agents and criminals form two distinct populations of short-lived and myopic agents. Policemen inspect would-be transgressors as long as they expect some of them to violate the law, but they quit inspecting when they realize that violations are almost never committed. However, if police do not inspect, then violations become more frequent and this brings about a new wave of inspections. The analogies with the oscillations of predator-prey relationships are obvious.

The hypothesis that *both* actors involved are myopic is not always realistic. There are cases in which police is best modelled as a single, forward-looking actor, who faces a large population of myopic would-be transgressors. Examples of this kind of interaction abound. Just think about the relationship between tax-auditors and tax-payers, or police crews and motorists on highways. The present paper asks the following question: should one expect to see more or less crime if the police force is a long-lived, forward-looking agent rather than a myopic one? (Neher [13] asks a similar question concerning the economics of crime.) One might conjecture that a forward-looking police force will not quit inspecting when law infractions become rare, because it anticipates that the number of infractions will rise again if it does. Hence one would predict no oscillations and a lower level of crime in equilibrium. This paper shows that this intuition is partially mistaken. Contrary to what one might expect, as the police force becomes more forward-looking, more crime, not less, might be observed in equilibrium. Some technical conditions at which such a counterintuitive phenomenon can take place are investigated. I will also show that these conditions are fulfilled by some of the games discussed in the literature, for example by Saha and Poole [14].

	Inspect	**Not Inspect**
Violate	a_{11},b_{11}	a_{12},b_{12}
Not Violate	a_{21},b_{21}	a_{22},b_{22}

Table 1: The Inspection Game

2 The inspection game

Consider the game in Figure 2. Player A must decide whether to $Violate$ a given law or a regulation. B is an inspector, or a police officer, who might $Inspect$ him. The entries of the two matrices satisfy the following inequalities: $a_{12} > a_{22}$ (violating the law is profitable if police does not inspect), $a_{21} > a_{11}$ (respecting the law is the best strategy if police inspect), $b_{11} > b_{12}$ (police prefers to inspect if the public violates the law) and $b_{22} > b_{21}$ (police rather not inspect if the public respects the law). Let p be the probability with which A plays $Violate$ and q the probability with which B plays $Inspect$. The game has a single mixed strategy Nash equilibrium:

$$(p^*, q^*) = \left(\frac{b_{22} - b_{21}}{b_{22} - b_{21} - b_{12} + b_{11}}, \frac{a_{22} - a_{12}}{a_{22} - a_{12} - a_{21} + a_{11}}\right) \tag{1}$$

Suppose now that the game is played repeatedly by pairs of individuals drawn at random from two large populations A (the public) and B (the police). In each population, strategies that yield a payoff larger than the average within that population are assumed to increase, crowding out strategies that yield lower-than-average payoffs. This might reflect a process of learning, imitation and so on. (See Weibull [18] for an accessible introduction to evolutionary models of this kind.)

Formally, let p and q be the fractions of A and B that play $Violate$ and $Inspect$ respectively. I will assume that the learning and imitation process will induce p and q to change over time according to the Replicator Dynamics (RD):

$$\dot{p} = p(1-p)(\pi_1^B(q) - \pi_2^B(q)) = \alpha p(1-p)(q^* - q) \tag{2a}$$

$$\dot{q} = q(1-q)(\pi_1^A(p) - \pi_2^A(p)) = \beta q(1-q)(p - p^*) \tag{2b}$$

where $\alpha \equiv -a_{22}+a_{21}+a_{12}-a_{11} > 0$ and $\beta = b_{22}-b_{21}-b_{12}+b_{11} > 0$. $\pi_i^A(p)$, $\pi_i^B(q)$ are the expected payoffs of adopting strategy i ($i = 1, 2$) in population A and B. It is a well known fact in evolutionary game theory that the fractions p and q oscillate constantly, although their averages converge to the equilibrium values p^* and q^*. (See Andreozzi [1] and Cressman e.a. [5] for an application of this result to the logic of law enforcement.)

3 Evolutionary policies

The evolutionary model in the previous section is based on the hypothesis that both populations are made of limitedly rational and myopic players. Suppose now that agent B is a a single organization (the police force, the tax authority and so on.) The frequency q with which it plays *Inspect* will now reflect the long term interest of this collective agent, instead of the aggregation of a multitude of individual (myopic) choices. Nothing changes in population A, whose internal dynamics is still represented by the differential equation (2a).

Since now B is a rational, forward-looking player, she will choose a path for the frequency $q(t)$ with which she plays *Inspect* that maximizes the actual value of the future stream of payoff:

$$\pi^B(p(t), q(t)) = b_{11}pq + b_{12}p(1-q) + b_{21}(1-p)q + b_{22}(1-p)(1-q)$$

subject to the constraint that the frequency $p(t)$ of law infractions varies according to (2a). Formally, B solves the following optimal control problem:

$$\max_q \left(\int_0^\infty e^{-rt}\pi^B(p(t), q(t))dt \right. \tag{3}$$

$$s.t. \qquad \dot{p} = \alpha p(1-p)(q^* - q)$$

$$p(0) = p_0 \in (0,1) \qquad q(t) \in [0,1] \qquad \forall t \in [0, \infty)$$

where r is B's time discount rate.[1] The current-value Hamiltonian for this problem is

$$H(p(t), q(t), m(t)) = \pi^B(p(t), q(t)) + m(t)[\alpha p(1-p)(q^* - q)] \tag{4}$$

where the costate variable $m(t)$ satisfies[2]:

$$\begin{aligned} \dot{m} &= rm - \frac{\partial H}{\partial p} = rm - \frac{\partial \pi}{\partial p} - m\alpha(1-2p)(q^* - q) \\ &= m(r - \alpha(q^* - q)(1-2p)) - \beta(q - q^+), \end{aligned} \tag{5}$$

where $q^+ \stackrel{def}{=} \frac{b_{22} - b_{12}}{b_{11} - b_{12} - b_{21} + b_{22}}$. A *stationary* optimal path is a triple $(\bar{p}, \bar{q}, \bar{m})$ such that $\dot{p} = \dot{m} = 0$ for $p = \bar{p}$, $q = \bar{q}$ and $m = \bar{m}$, while for every $q \neq \bar{q}$, $H(\bar{p}, \bar{q}, \bar{m}) > H(\bar{p}, q, \bar{m})$. If initially $p_0 = \bar{p}$, a rational inspector B maximizes his payoffs by setting $q = \bar{q}$, so that $\dot{p} = \dot{m} = 0$.

Lemma 1 *The optimal control problem (3) has a unique stationary optimal path:*

$$\bar{q} = q^*; \tag{6}$$

$$\bar{m} = \frac{\beta(q^* - q^+)}{r}; \tag{7}$$

$$\bar{p} = \frac{-(\bar{m}\alpha - \beta) - \sqrt{(\bar{m}\alpha - \beta)^2 + 4\bar{m}\alpha\beta p^*}}{2\bar{m}\alpha} \tag{8}$$

[1] Notice that the initial fraction of law infractions p_0 has been restricted to the open interval $(0,1)$. This is to avoid that the population gets locked in a steady state in which $\dot{p} = 0$ even if the two pure strategies yield different payoffs.

[2] Consider that it is easy (if tedious) to show that $\frac{\partial \pi}{\partial p} = \beta(q - q^+)$.

Proof. To see that $(\bar{q}, \bar{m}, \bar{p})$ is a stationary optimal path for the control problem (3) consider first that for any $p \in (0,1)$, $\dot{p} = 0$ iff $q = q^*$. If $q = q^*$, then equation (5) reduces to $\dot{m} = rm - \beta(q^* - q^+)$, and hence

$$\dot{m} = 0 \Longleftrightarrow m = \frac{\beta(q^* - q^+)}{r} = \bar{m} \tag{9}$$

Since $\bar{q} = q^*$ is an interior solution, we must have

$$\frac{\partial H(p,q,m)}{\partial q} = \beta(p - p^*) - \bar{m}\alpha p(1-p) = 0 \tag{10}$$

that is $\bar{m}\alpha p^2 + p(\beta - \bar{m}\alpha) - \beta p^* = 0$. The roots of this equation are:

$$p_{12} = \frac{-(\bar{m}\alpha - \beta) \pm \sqrt{(\bar{m}\alpha - \beta)^2 + 4\bar{m}\alpha\beta p^*}}{2\bar{m}\alpha}. \tag{11}$$

It can be easily shown that the smaller of the two roots lies in the interval $[0,1]$. This is the only value of p that satisfy the optimality condition (10) and the restriction on the state variable $p \in (0,1)$. This completes the first part of the proof.

To see that $(\bar{p}, \bar{q}, \bar{m})$ is the only stationary optimal path, consider that for $q \neq q^*$ $\dot{p} = 0$ iff $p = 0$ or $p = 1$. However, if $p_0 \in (0,1)$, then p cannot reach either 0 or 1 in a finite time (because $\dot{p} \to 0$ as p approaches the borders of the interval $[0,1]$), so that if $q \neq q^*$ then $\dot{p} \neq 0$ for all t. This completes the proof. ■

The Hamiltonian (4) is linear in the control variable q and has a single interior stationary optimal path.[3] This implies that the optimal control problem 3 in the general case in which $p_0 \neq \bar{p}$, has a particularly simple solution: B must choose q in such a way that the state variable p approaches its optimal stationary value $\bar{p}$ in the shortest time. This is the content of the following:

Proposition 2 *1.The optimal strategy S for the long run inspector B is:*
a) if $p < \bar{p}$, then $q = 0$;
b) if $p > \bar{p}$, then $q = 1$;
c) if $p = \bar{p}$, then $q = q^*$.
2. Under the optimal strategy S, from any initial condition $p_0 \in (0,1)$ population A reaches its stationary optimal path level $\bar{p}$ in a finite time $\bar{t}$. After that time, B sets $q = q^*$ so that p remains fixed at $\bar{p}$.

Proof. 1. Because of the linearity of the Hamiltonian (4), the optimal path is the one that minimizes the time spent out of the optimal stationary path $(\bar{p}, \bar{q}, \bar{m})$. (Proofs of this fact can be found in Kamien and Schwarts [9], section 16, Takayama [15] and Clark [4].) Since $\arg\max_q(\dot{p}) = 0$ and $\arg\min_q(\dot{p}) = 1$, if $p < \bar{p}$ ($p > \bar{p}$), the optimal policy for B is to set $q = 0$ ($q = 1$). On the other hand, if $p = \bar{p}$, then $q = q^*$ so that $\dot{p} = 0$.

[3]To see that the Hamiltonian in linear in q consider that the inspector's payoff function $\pi^B(.,.)$ is linear both in p and in q, and that RD is linear in q, although not in p.

2. Suppose that $p_0 < \bar{p}$ (the case $p_0 > \bar{p}$ can be treated similarly). In this case B will set $q = 0$, so that equation (2a) reduces to a simple logistic equation

$$\dot{p} = p(1-p)q^* \tag{12}$$

that can be integrated

$$p(t) = \frac{1}{1 - \exp(k - q^* t)}, \tag{13}$$

where $k = \log \frac{(p_0 - 1)}{p_0}$. It follows that the time it takes to bring p to its optimal level $\bar{p}$ is

$$\bar{t} = \frac{1}{q^*}[k - \log(\bar{p} - 1)]. \tag{14}$$

which is bounded away from ∞. After a time $\bar{t}$, B will set $q = q^*$ so that $\dot{p} = 0$. ■

Proposition 2 shows that population A will spend most of the time at $\bar{p}$, because the inspector will minimize the time it spends outside this state. Hence, it is interesting to see how changes in the police's time discount rate r affect $\bar{p}$.

Proposition 3 *(a) The optimal stationary value $\bar{p}$ converges to the stage game Nash equilibrium value $\bar{p} \to p^*$ as $r \to \infty$; (b) $\bar{p} > p^*$ and $\bar{p} \to 1$ as $r \to 0$ if $q^* > q^+$; (c) $\bar{p} < p^*$ and $\bar{p} \to 0$ as $r \to 0$ if $q^* < q^+$.*

Proof. a) If $r \to \infty$, $\bar{m} = \frac{\beta(q^* - q^+)}{r} \to 0$. Recall that $\bar{p}$ is the smallest root of $\bar{m}\alpha p^2 + p(\beta - \bar{m}\alpha) - \beta p^* = 0$, which for $\bar{m} \to 0$ reduces to $p\beta - p^*\beta = 0$, whose only root is $p = p^*$.

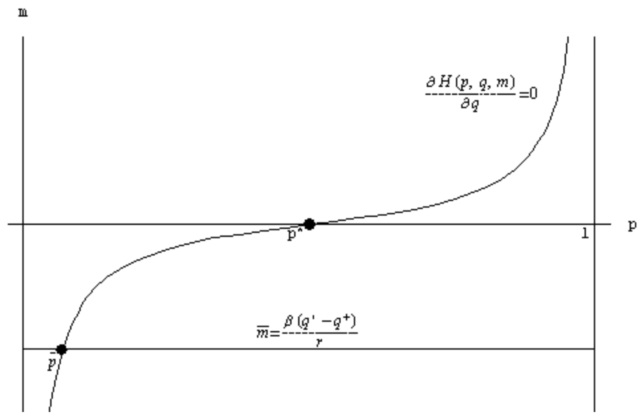
b) If $r \to \infty$, $\bar{m} = \frac{\beta(q^* - q^+)}{r} \to +\infty$ if $q^* > q^+$. Let rewrite condition (10) as

$$\bar{m}\alpha = \frac{-\beta(p - p^*)}{p(1-p)} \tag{15}$$

The left hand side approaches ∞ as $\bar{m} \to +\infty$ and hence $p \to 1$ (If $p \to 0$, then the right hand side would approach $-\infty$). Similarly, the left hand side approaches minus infinite as $\bar{m} \to +\infty$, so that $p \to 0$. ■

Proposition 3 is the core of the paper. It proves that if the inspector is rational, but myopic ($r \to \infty$), it will keep the frequency of law violations around its Nash equilibrium value p^*. This is not surprising: if $p > p^*$, the inspector gets a larger payoff if she plays *Inspect*. In so doing, however, she reduces the frequency of law infractions p until it reaches the Nash equilibrium level p^*. At this point *Inspect* and *Not Inspect* yield the same payoff. Similarly, if initially $p < p^*$, a myopic inspector will play *Not Inspect* because it yields a larger immediate payoff than *Inspect*. However, this will increase the frequency of violations p until it reaches p^*.

When the inspector becomes more forward looking, ($r \to 0$) it will take into consideration the future effects of her current choices. Since he will not play the strategy that yields the larger immediate payoff, the optimal level of crime



violations $\bar{p}$ will be different from p^*. The interesting result of this analysis is that increasing r will not necessarily reduce $\bar{p}$ below p^*. Proposition 3 shows that this will happen only provided that $q^* < q^+$. When the opposite inequality holds true, a more forward looking inspector will tolerate more crime than a short-sighted one.

4 Conclusions

Andreozzi [2] discusses a variant of the inspection game in which the inspector can act as a Stackelberg leader of the game and he obtains a result similar to those presented in Proposition 3. He shows that if the inspector can commit himself to a probability of inspection, he will induce player A to play $Violate$ if $q^* > q^+$ and to play $Not\ Violate$ if $q^* < q^+$. The present paper extends this result to the case in which the inspector (who cannot commit to a probability of inspection) is a long-run player facing a large population of short-sighted opponents, in the the spirit of Fudenberg and Levine [7] [8]. All the consequences of this result for the economic approach to law enforcement are discussed in Andreozzi [2] and will not be repeated here.

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