ARE EQUILIBRIUM STRATEGIES UNAFFECTED BY INCENTIVES?

THE POLICE GAME

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Working Paper #595
August 1990

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Abstract

When a matrix game has an equilibrium in mixed strategies, changing one player's payoffs affects only the other player's equilibrium strategy mix. We call this the Payoff-Irrelevance Proposition (PIP). The PIP, it has been contended, undercuts the main foundations of economic policy analysis. A policy-maker who attempts to influence behavior by adjusting costs and benefits will fail, assertedly, since equilibrium behavior will not respond to changes in incentives. We show, in contrast, that: (1) Policy interactions usually should be modelled as a sequential-move Stackelberg game, the policy-maker having the first move, in which case the PIP does not hold. (2) Even in a simultaneous-move game, the PIP almost always fails if the strategy space is a continuum. (3) Even in a simultaneous-move game with discrete policy options, the PIP holds only if the payoff adjustments are sufficiently small. Thus, except for a narrow set of conditions, the PIP is generally inapplicable; incentives do generally affect behavior in equilibrium.

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In a mixed-strategy Nash equilibrium of a non-cooperative game, each player's equilibrium probability mixture depends only upon the other player's payoffs. A series of papers by George Tsebelis [1989, 1990a, 1990b] use this well-known theorem to draw some startling inferences about policies aimed at deterring undesired actions. Among the assertions are that: (1) in crime control, increasing the size of penalties will not reduce the number of offenses; (2) in international affairs, imposing economic sanctions will not lead the targeted nation to modify its actions; and (3) in hierarchical systems, monitoring will not improve the behavior of subordinates. The policy-maker, despite being able to influence the payoffs, supposedly cannot affect the actual equilibrium choice (mixed strategy) of the affected parties. We will call this assertion the Payoff-Irrelevance Proposition (PIP).

The PIP, if valid, evidently undercuts economic reasoning on issues of regulation of behavior. In analyzing the trade-off between probability of detection and size of penalties, for example, Becker (1968) and Ehrlich (1973) presumed that incentives do affect the choices of rational criminals; their analyses become irrelevant if sanctions do not affect what criminals do. The PIP does not imply that policy is totally useless, however. Thus, if criminal penalties are increased, while the PIP predicts that the amount of crime will not change, the police may be able to economize by investing less effort in enforcing the laws. Nevertheless, to the extent that the PIP applies, the usual arguments for and against policy measures like criminal sentencing, tariffs, taxes, subsidies, and regulations are gravely weakened.[1]

Rising to the challenge, we will show that the PIP holds only in very special and indeed limiting cases, so that the foundation of the economic approach to policy -- the premise that incentives affect the equilibrium behavior of impacted parties -- is solid after all. While other critics have argued that policy situations ought to be modelled as repeated games or that two-person games are unrealistic (Bianco et al, 1990), our analysis is based upon the number and range of allowed strategies and the order of moves. Our objection is not that the PIP fails to generalize, but that it is rarely if ever applicable even to the simple situations it purports to describe.

I. THE POLICE GAME AND THE PAYOFF-IRRELEVANCE PROPOSITION (PIP)

In the characteristic situation described by Tsebelis, the police are the policy-making authority, choosing between patrolling to enforce the law and not patrolling (strategies P and NP). The potential offenders or criminals choose between committing and not committing crimes (strategies C and NC). Table 1 shows the respective payoffs abstractly. Following Tsebelis' assumptions, for the criminals $c_4>c_3$ and $c_2>c_1$ while for the police $p_4>p_3$ and $p_2>p_1$. (The criminals will choose C if they know the police are not patrolling, but NC if the police are patrolling; the police will choose P if they anticipate that crimes will be committed, but NP if they do not expect any offenses.) Table 2 is a numerical illustration

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[1] There is a seeming resemblance between the Payoff-Irrelevance Proposition and some "rational expectations" theorems (see, for example, Barro [1974] on the ineffectiveness of fiscal policy). But the similarity is superficial only. The rational expectations argument is that policy is ineffective <u>because it has been fully anticipated</u>; strategic uncertainty is not involved. The Payoff-Irrelevance Proposition, in contrast, is based upon the nature of the mixed-strategy equilibrium under strategic uncertainty.

consistent with these specifications, bigger numbers representing more desired outcomes.

[TABLES 1 AND 2 ABOUT HERE]

This is a discoordination game, with no Nash equilibrium in pure strategies. As the arrows in the Tables indicate, one player or the other will want to deviate from any combination of pure strategies. Following standard procedures, the mixed-strategy equilibrium (where π_c is the probability with which criminals use their C strategy and π_p is similarly the probability with which police use their P strategy) is given by:

(1)
$$\pi_c = (p_4 - p_3)/(p_2 - p_1 + p_4 - p_3)$$
$$\pi_p = (c_4 - c_3)/(c_2 - c_1 + c_4 - c_3)$$

It is easy to verify that, for the specific numerical matrix of Table 2, $\pi_c = \pi_p = 1/2$.

Equations (1) show the Payoff-Irrelevance Proposition at work. The probability mixture chosen by the criminals is a function only of the payoffs of the police, and that of the police is a function only of the criminals' payoffs. If penalties for crime were increased, therefore (that is, if c_1 were reduced), π_c would remain the same -- the amount of crime would be left unchanged. Only π_p would change.

II. SIMULTANEOUS VERSUS SEQUENTIAL PLAY

The first substantive issue to be addressed is whether the Police Game ought to be modelled in terms of a simultaneous-play or a sequential-play protocol. Or, put another way, can both sides be expected to behave strategically, or only one?

In the nature of the case, policy-makers have to reason strategically. The police, in deciding whether to allocate more resources to the south side of town than to the north side, must rationally ask themselves how potential offenders would respond. If the decision is to patrol the north end of town more heavily, the criminals, it can usually be anticipated, will find out and shift their depredations to the south end of town.[2] The criminals, on the other hand, as individually small actors, are normally like "price-takers" in microeconomic theory. An individual offender could not reasonably say to himself, "If I shift to the south end of town, the police will simply come after me there, so I won't derive any advantage." Most criminal activities -- from murder and theft to fraud and insider trading -- remain in the sphere of competitive, decentralized actions. (As an evident exception, however, if crime were cartelized through a Mafia-type organization, both the police and the criminal planners would have to play strategically.)

Setting this exception aside, the Police Game should normally be analyzed in terms of a sequential-play protocol. The authorities make the initial move, premised on the belief that the criminals will individually respond rationally. The solution corresponds to the Stackelberg equilibrium of duopoly theory (rather than to the simultaneous-move Cournot equilibrium). Specifically, we see in Table 1 that, having the first move, the police would choose P if $p_3 > p_1$ and NP if the opposite holds. That is, the police would enforce the law if they prefer the outcome "Patrol, Not commit" over "Not patrol, Commit" -- while if their preferences were

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[2]The authorities may well attempt to publicize their actions. One of us recently heard a radio ad of the Chicago Transit Authority advising criminals (presumably, truthfully) that enforcement levels had been increased.

reversed, they would not patrol. We might expect the police to normally have the first of these rankings ($p_3>p_1$, as in Table 2), with the desirable consequence that all crimes are deterred. But given the cost of patrolling this may not always be the case. As an economic choice, the community in general and the police as their representatives routinely tolerate relatively minor crimes such as possession of small amounts of marijuana. For such offenses they may prefer "Not patrol, Commit" -- $p_1>p_3$.[3] Whichever way the ordering goes for different types of offenses, the crucial point is that *in the Stackelberg equilibrium, each party's optimum is a pure strategy, the choice of which does indeed depend upon his/her own payoffs*. The Payoff-Irrelevance Proposition fails.[4] There is always an equilibrium in pure strategies,[5] and each party's preference ranking *will* affect his or

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[3] Instead of the numbers in Table 2, for example, the police payoffs could be:

	NP	P
NC	4	1
C	2	3

Here $p_1 = 2$ exceeds $p_3 = 1$.

[4] Tsebelis (p. 83) concedes that, in the Police Game, it is "more realistic" to assume that the police have the first move, so that the conditions for the Stackelberg equilibrium apply. But he incorrectly asserts that the Stackelberg solution will be the *same* as the solution to the simultaneous-play game. His reasoning appears to be based on the premise that the police, although having the first move, would find it advisable to keep their strategy choice secret. This would in effect throw the parties back into the simultaneous-move game, with the same solution as before. But secrecy (giving up the first move) is not *generally* more profitable than making the first move and openly announcing it. In the numerical illustration of Table 2, for example, the best sequential play leads to the outcome "Patrol, Not commit" with a payoff to the police of $p_3 = 3$. The simultaneous-play equilibrium $\pi_c = \pi_p = 1/2$ achievable under secrecy has a payoff to the police of only 2 1/2. Thus, in this case, the police would be unwise to sacrifice the advantage of the first move.

[5] Where a tie exists so that preferences are not strictly ordered, there might also be mixed-strategy solutions. If two pure strategies are both optimal for a player, then so are any probability mixtures thereof.

her decision.

This conclusion will be stated as our first listed result:

RESULT #1: The Payoff-Irrelevance Proposition is invalid for sequential-move games.

Since in most public policy situations the constituted authorities are in the position of making decisions that will be impacting many individually small actors, the relevant model involves the sequential-play protocol and the associated Stackelberg equilibrium condition. So the Payoff-Irrelevance Proposition, limited as it is to interactions characterized by the simultaneous-play protocol and the Cournot equilibrium condition, does not after all undermine the foundations of policy analysis.

III. SIMULTANEOUS-PLAY EQUILIBRIUM WITH A STRATEGY CONTINUUM

In the preceding section we indicated that policy-makers normally will be playing a sequential-move rather than a simultaneous-move game with the affected parties. There are, however, a number of important exceptions, among them: (1) when the targeted player is as much of a centrally organized entity as the policy-makers themselves, and (2) where the policy-makers, although having the option of the first move, find it more advantageous to act secretly. In this section we will be postulating that one or the other of these exceptions applies, so that the simultaneous-move protocol is indeed applicable. Even so, we shall see, the Payoff-Irrelevance Proposition (PIP) has only a limited range of applicability.

A natural way to approach the simultaneous-move Police Game is to postulate that both police and criminals can choose over a strategy continuum. Instead of the restriction to the discrete options C and NC on the one side and P and NP on the other, let criminals choose crime level $0 \le C \le 1$ while the police simultaneously choose patrolling level $0 \le P \le 1$.

A standard method of solution for games with continuous strategy spaces is to determine the Reaction Curves showing each side's optimal action as a function of the other's choice. The intersection of the Reaction Curves represents the simultaneous-play Nash-Cournot equilibrium.

Some simple examples will be illuminating. Let the payoff or value functions, to criminals and police respectively, be:

$$\begin{aligned} V_c &= \alpha_c C - \beta_c C^2/2 - \gamma_c P \\ V_p &= \alpha_p P - \beta_c P^2/2 - \gamma_2 C \end{aligned} \qquad (2)$$

where the Greek letters signify positive parameters.

The Reaction Curves are:[6]

$$\begin{aligned} RC_c&: \quad C = \alpha_c/\beta_c \\ RC_p&: \quad P = \alpha_p/\beta_p \end{aligned} \qquad (3)$$

In this case the chosen level of crime C will depend only upon α_c and β_c, increasing as the criminals' "gain parameter" α_c increases and decreasing as their "diminishing returns parameter" β_c rises. Similarly the patrolling effort P will depend only upon the police "gain parameter" α_p and "diminishing returns" parameter β_p. As shown in Figure 1, the criminals' Reaction Curve RC_c is a horizontal line while the police Reaction Curve RC_p is a vertical line. The point of this exercise is that, to the exact contrary of the Payoff-Irrelevance Proposition, <u>here each side's optimal choice depends solely upon its own payoff parameters and not</u>

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[6] Found by setting the first derivatives $\partial V_c/\partial C$ and $\partial V_p/\partial P$ equal to zero and solving for C and P.

<u>at all upon the opponents' payoffs</u>.[7]

[FIGURE 1 ABOUT HERE]

While payoff function (2) is a special case, the main point -- that a player's optimum strategy does depend his/her own payoffs -- is quite general. Typically, the Reaction Curves will be sloping as illustrated in Figure 2, so that the equilibrium continuous-strategy optimum for each player involves the payoff parameters of both sides. Consistent with the spirit of the Police Game and the payoff restrictions shown in Table 1, the criminals' Reaction Curve RC_c should be negatively sloped: as the police increase patrolling, the criminals prefer a lower level of criminal activity. And, correspondingly, the police Reaction Curve RC_p should be positively sloped: as offenders increase C, the police would prefer a higher level of patrolling.

The illustration in Figure 2 is based upon the payoff functions:[8]

$$(4) \qquad \begin{aligned} V_c &= \alpha_c C - \beta_c P C^2/2 \\ V_p &= -\alpha_p P - \beta_p C/P \end{aligned}$$

[FIGURE 2 ABOUT HERE]

The implied Reaction Curves are:

$$(5) \qquad \begin{aligned} RC_c&: \quad C = \alpha_c/\beta_c P \\ RC_p&: \quad P = (\beta_p C/\alpha_p)^{1/2} \end{aligned}$$

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[7]The criminals are maximizing V_c with respect to C while the police are maximizing V_p with respect to P. It is easy to see that the first derivative $\partial V_c/\partial C$ does not depend upon P, and similarly $\partial V_p/\partial P$ does not depend upon C.

[8]These payoff functions retain the desirable property that the "marginal products" (of C to the criminals and of P to the police) are always diminishing.

And the equilibrium levels of C and P, obtained by solving equations (5) simultaneously, are:

$$(6)\qquad \begin{aligned} C^* &= (\alpha_c{}^2\alpha_p/\beta_c{}^2\beta_p)^{1/3} \\ P^* &= (\alpha_c\beta_p/\alpha_p\beta_c)^{1/3} \end{aligned}$$

The solid curves in Figure 2 correspond to the parameter values $(\alpha_c, \beta_c, \alpha_p, \beta_p) = (1, 4, 2, 1)$. The equilibrium strategy-pair, in pure strategies of course, is then $C^* = P^* = 1/2$. That each party's equilibrium choice does depend upon his/her own as well as upon the other's payoff parameters is evident from the form of equations (6). If for example the criminal "gain parameter" α_c rises from 1 to 2, the criminals' Reaction Curve shifts upward as illustrated by the dashed curve in the diagram. At the new solution, $(C^*, P^*) = (.7937, .6300)$. Thus, an increase in criminal payoffs has led to a rise in both the amount of crime and the amount of patrolling.

Summarizing:

RESULT #2: The Payoff-Irrelevance Proposition is generally invalid even for simultaneous-move games, if the strategy space for both players is a continuum.[9]

The paradoxical PIP result, we can now see, is essentially an artifact due to lumpiness. Rational choices rely on trade-offs; lumpiness of the options available reduces what can be done in the way of trade-offs. Suppose someone currently finds eggs too expensive to purchase. Even if the price falls, if the choice is between taking a dozen eggs or no eggs at all,

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[9] A technical qualification: the Reaction Curves must actually intersect in the interior of the strategy space. Sufficient conditions for such an intersection are that the strategy sets be compact and convex, and that a player's payoff is quasi-concave in his own strategy (see Rasmusen, 1989, pp. 124-125).

such a consumer may still take none -- whereas, offered the opportunity of buying single eggs, two or three might be bought instead. Similarly, a choice between a discrete C or NC is less susceptible to influence than if the available options covered all the gradations in between.

III. SIMULTANEOUS-PLAY EQUILIBRIUM WITH DISCRETE STRATEGIES

Still under the simultaneous-play protocol, suppose now that while the underlying situation remains the continuous-strategy space of Figure 1 or 2, for some reason only selected discrete options rather than the entire continuum are available to the parties. Only in this case, as will be seen, is the Payoff-Irrelevance Proposition (PIP) possibly valid. It will be convenient to state the result first, with the development to follow.

RESULT #3: The Payoff-Irrelevance Proposition <u>may</u> be valid for simultaneous-move games if the strategy space is discrete, provided that the payoff changes are "sufficiently small" (in a sense to be made precise below).

Let equation (4) continue to represent the payoff functions, as in our previous illustration. But now suppose that the parties can no longer choose C and P over the continuum. Instead, C for the criminals and P for the police must be chosen from the set {.2, .4, .6, .8, 1}. As can be seen in Figure 2, the strategy options .4 and .6 for each side are the "immediate neighbors" bracketing the continuous-strategy equilibrium choices $C^* = P^* = .5$ (choices that are no longer available). It is a plausible procedure, valid here though unfortunately not universally correct, to consider only these immediate neighbors as candidates for a possible mixed-strategy equilibrium.[10]

Table 3 illustrates the entire range of payoffs, while Table 4 is a condensation showing only the immediate-neighbor options: $C \in (.4, .6)$ and $P \in (.4, .6)$.[11] There is no pure-strategy equilibrium for this game. Using equations (1) to find the equilibrium mix of the two neighboring strategies, over the strategy sets (.2,.4,.6,.8,1) the equilibrium mixtures are: for the criminals, $\pi_c = (0,.6,.4,0,0)$ and for the police $\pi_p = (0,.545,.455,0,0)$.

Thus we have shown by construction that a mixed-strategy equilibrium is possible given a discrete strategy space for the Police Game. That a mixed-strategy outcome is not inevitable is illustrated in Table 5. Here the available strategy options are, by assumption, .4 and 1.0 on each side. (Whereas Table 4 was a condensation of the underlying Table 3 showing the strategies entering into the equilibrium mixture on each side, Table 5 is quite different. Now we are dealing with a quite different game where, by assumption, all but the two specified strategies on each side have been disallowed.) In Table 5, $C^* = P^* = .4$ is a pure-strategy equilibrium.

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[10] More extreme pure strategies might enter into a mixed-strategy equilibrium, even conceivably in place of a "neighboring" strategy, since the payoff functions might take on any of a wide variety of forms. The payoff functions need not necessarily be monotonic or even bitonic in the C and P variables, and the interaction can be formulated in many different ways.

[11] Table 4 is an allowable condensation, since in Table 3 all but the .4 and .6 row and column strategies can be ruled out by iterated strict dominance considerations. Specifically: (1) the $P = 1$ and $P = .2$ columns can be deleted as they are dominated by $P = .8$ and $P = .4$ respectively; (2) then the $C = .2$ row is dominated by $C = .4$, and $C = .8$ and $C = 1$ are both dominated by $C = .6$; (3) and finally, the $P = .8$ column is then dominated by $P = .6$. This process leaves only the .4 and .6 strategies on each side.

These results suggest that there is likely to be a pure-strategy equilibrium when the available choices are asymmetrically placed -- one of the strategy-pairs being located close to and the others far away from the pure-strategy equilibrium choices of the underlying continuum. Conversely, when the available choices are more or less evenly distant from the equilibrium of the continuous game, a mixed-strategy equilibrium is likely.[12]

Finally, let us return to the claim that the Payoff-Irrelevance Proposition holds at least within the window of conditions leading to mixed-strategy equilibria. Intuition suggests that, if the equilibrium strategy mixture is not to be affected, only payoff changes within a limited range are allowable. More specifically, our previous analysis suggests that for such insensitivity to hold, the payoff parameter variations must be small enough so as not to cause a shift either to a pure-strategy equilibrium or to a mixed equilibrium involving different strategy elements.

Looking at Figure 2, the continuous-strategy intersection involving the dashed RC_c curve was generated by a change in the criminals' gain parameter from $\alpha_c = 1$ to $\alpha_c = 2$. Is this change "sufficiently small" for insensitivity to hold in the discrete-strategy game described above, where the options on each side ranged from .2 to 1 in steps of .2 each? That is, for the criminals' optimal strategy to remain the mixture of $C = .4$ and $C = .6$ with probabilities .6 and .4 respectively? Notice that the intersection involving the new RC_c curve no longer lies between .4 and .6, which may lead us to suspect that this parameter change is not "sufficiently

[12]This is only a tendency rather than a strict rule, since (as previously noted) distance as measured in the strategy space need not correlate well with distance in terms of the payoffs.

small" to leave the criminals' optimum mix unaffected. And in fact, Table 6 -- like Table 3 but calculated in terms of the criminal "gain parameter" $\alpha_c = 2$ instead of $\alpha_c = 1$ -- reveals that there is now a pure-strategy equilibrium at $C* = .8$, $P* = .6$. (The shift to a pure-strategy solution is not surprising, since, with the changed α_c parameter, this discrete strategy-pair is very close to the equilibrium of the continuous-strategy game at $C* = .7937$, $P* = .6300$.)

Thus, we have verified Result #3 by example. In particular, we have shown that, with a discrete strategy space, there may or may not be a mixed-strategy equilibrium. If there is a mixed-strategy equilibrium, then the PIP will be valid only for payoff changes that are "sufficiently small" in the sense of not affecting the strategies entering into the equilibrium mixture.

V. CONCLUSION

In two-strategy simultaneous-move games with a mixed-strategy equilibrium, a change in one player's payoffs affects only the other player's equilibrium mix. We call this the Payoff-Irrelevance Proposition (PIP). It has been alleged that the PIP vitiates the economic arguments for or against policy initiatives, since these run in terms of the effects upon incentives. While policy-makers can affect payoffs, changes in payoffs allegedly do not modify the equilibrium strategy mix of the impacted parties. In particular, in the Police Game an increase in penalties will assertedly not affect the criminals' mix between committing and not committing crimes.

In this paper we showed that:

1. Policy-making is ordinarily better modelled in terms of a sequential-move protocol (the authorities having the first move) and the associated Stackelberg solution rather than a simultaneous-move protocol and the Cournot solution concept. In sequential-move games the PIP will not apply; changes in incentives will affect the equilibrium behavior of the impacted party.

2. Even in the simultaneous-move game, if the strategy space is a continuum then once again the PIP will not be valid.

3. The PIP may apply only when the strategy space consists of discrete options; when choices are lumpy, a game may not have a pure-strategy equilibrium. Even when the PIP does apply, it holds only for payoff changes that are "sufficiently small" -- in the sense of not shifting the strategy elements entering into the equilibrium.

We conclude that, except for a narrow set of conditions, the PIP is generally invalid. Incentives do generally affect behavior in equilibrium.

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TABLE 1

PAYOFFS IN THE 2×2 POLICE GAME

Police

Criminals		NP		P
	NC	c_3,p_4	←	c_2,p_3
		↓		↑
	C	c_4,p_1	→	c_1,p_2

$c_4 > c_3, \quad c_2 > c_1$

$p_4 > p_3, \quad p_2 > p_1$

TABLE 2

THE 2×2 POLICE GAME-NUMERICAL EXAMPLE

Police

Criminals		NP		P
	NC	3,4	←	2,3
		↓		↑
	C	4,1	→	1,2

TABLE 3

THE POLICE GAME WITH FIVE DISCRETE STRATEGIES

Police

Criminals		.2	.4	.6	.8	1
	.2	.184,-1.4	.168,-1.3	.152,-1.533	.136,-1.85	.12,-2.2
	.4	.336,-2.4	.272,-1.8	.208,-1.867	.144,-2.1	.08,-2.4
	.6	.456,-3.4	.312,-2.3	.168,-2.2	.024,-2.35	-.12,-2.6
	.8	.544,-4.4	.288,-2.8	.032,-2.533	-.244,-2.6	-.48,-2.8
	1	.6,-5.4	.2,-3.3	-.2,-2.867	-.6,-2.85	-1,-3

TABLE 4

STRATEGIES OF TABLE 3 THAT ARE USED IN EQUILIBRIUM

		Police	
		.4	.6
Criminals	.4	.272,-1.8	.208,-1.867
	.6	.312,-2.3	.168,-2.2

TABLE 5

A TRUNCATED STRATEGY SET FROM TABLE 3

		Police	
		.4	1
Criminals	.4	.272,-1.8	.08,-2.4
	1	.2,-3.3	-1,-3

TABLE 6

TABLE 3 WITH INCREASED CRIMINAL GAIN PARAMETER

		Police				
		.2	.4	.6	.8	1
Criminals	.2	-.384,-1.4	.368,-1.3	.352,-1.533	.336,-1.85	.32,-2.2
	.4	.736,-2.4	.672,-1.8	.608,-1.867	.544,-2.1	.48,-2.4
	.6	1.056,-3.4	.912,-2.3	.768,-2.2	.624,-2.35	.48,-2.6
	.8	1.344,-4.4	1.088,-2.8	.832,-2.533	.576,-2.6	.32,-2.8
	1	1.6,-5.4	1.2,-3.3	.8,-2.867	.4,-2.85	0,-3

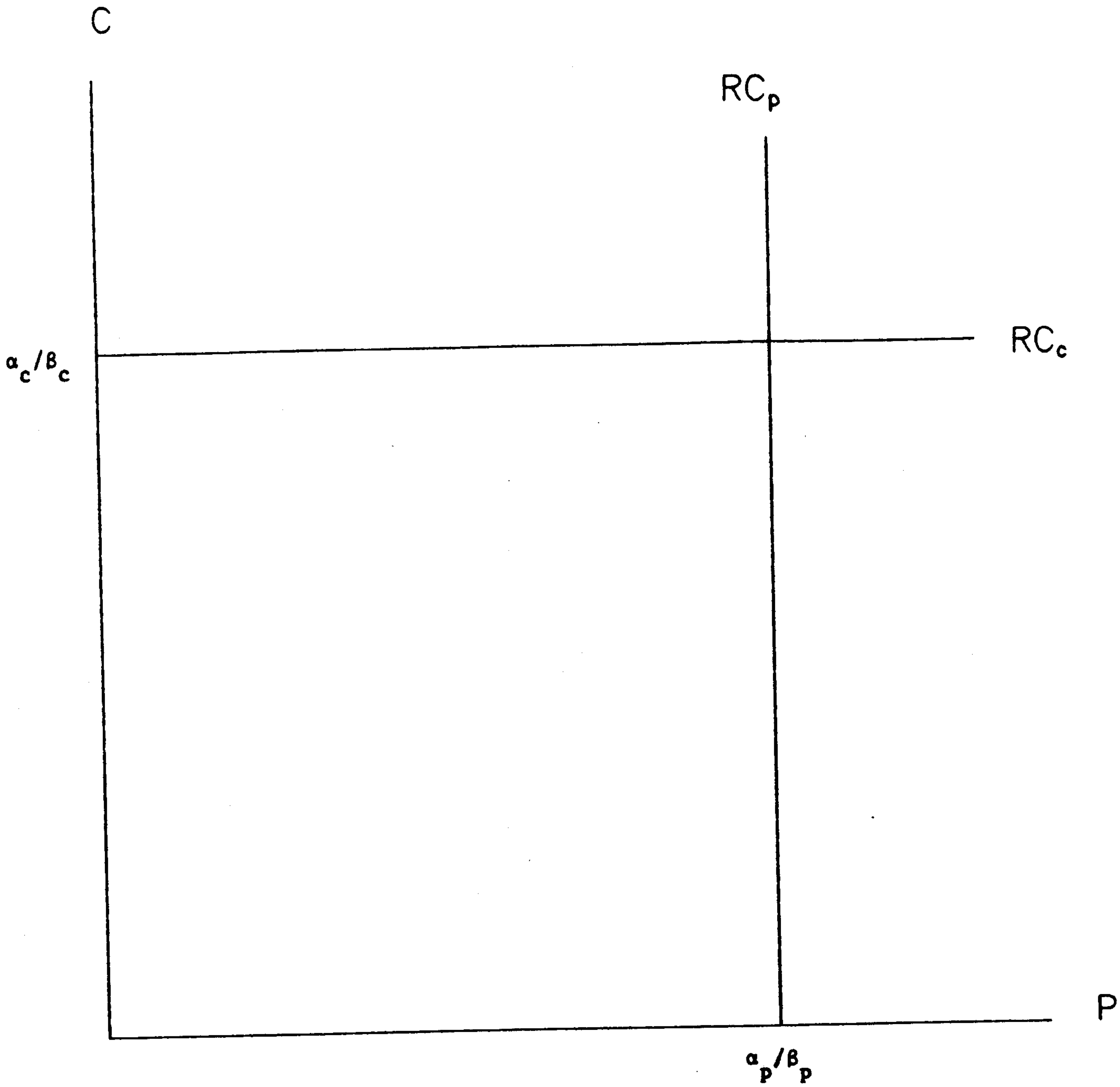

Figure 1: Simultaneous–move Police Game with strategy continuum: Strategy choices depend upon own payoff parameters only.

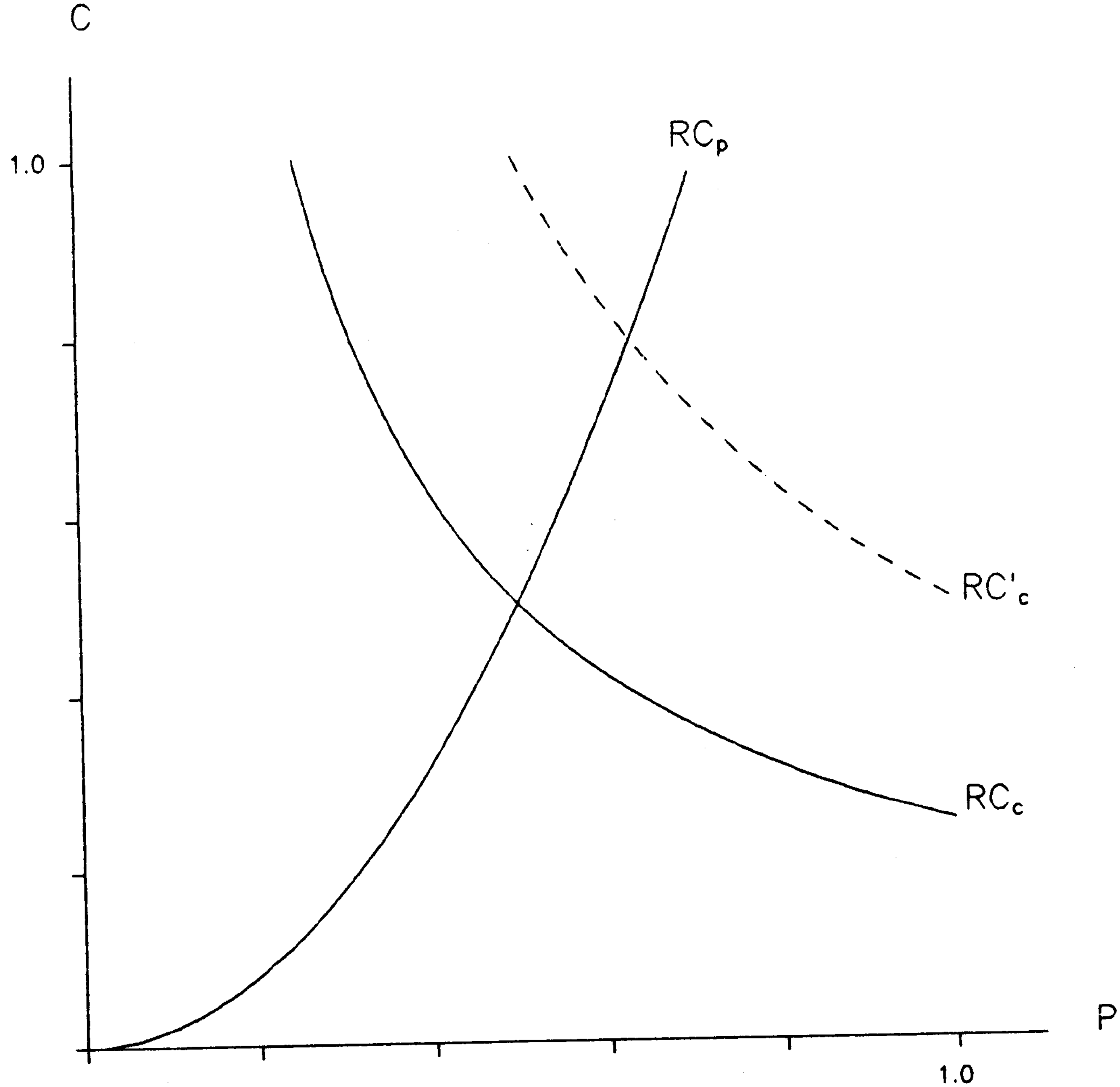

Figure 2: Simultaneous–move Police Game with strategy continuum: Strategy choices depend upon both sides' payoff parameters.