

DIVISION OF THE HUMANITIES AND SOCIAL SCIENCES
CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91125

COOPERATIVE INSTITUTIONS FOR INFORMATION SHARING IN
THE OIL INDUSTRY

R. Mark Isaac



SOCIAL SCIENCE WORKING PAPER 308

March 1980

COOPERATIVE INSTITUTIONS FOR INFORMATION
SHARING IN THE OIL INDUSTRY*

R. Mark Isaac

ABSTRACT

Exploration for oil and natural gas often produces an information externality for other resource owners. In isolation, this arrangement can lead to suboptimal exploration patterns. However, private institutions have evolved in the oil industry to provide markets for the external information. In this paper, the exploration process is modeled in a game theoretic framework in which the existence and performance of the private trading institutions are examined.

*This research was written partly while the author was funded by the John Randolph Haynes and Dora Haynes Foundation and partly while funded by the Caltech Energy Policy Project. Many helpful comments were received from Professors John Ferejohn, Roger Noll, and James Quirk, and from the Economic Theory Workshop.

COOPERATIVE INSTITUTIONS FOR
INFORMATION SHARING IN THE OIL INDUSTRY

R. Mark Isaac
California Institute of Technology

I. INTRODUCTION

Finding and producing petroleum is an inherently risky undertaking. In such an environment of uncertainty, information can be a valuable commodity.¹ There are several ways in which an oil firm can obtain information about a prospect. There are well defined markets in which certain scientific measurements or records can be obtained (aerial photographs, seismic surveys, the labor market for geologists and geophysicists, etc.). But, it is also true that the actual drilling, logging, coring, and producing from a subsurface structure can provide information.²

An important feature of petroleum exploration and development is that information obtained about one geological feature is often useful outside of a particular drilling site. Such information can give a better picture not only of a portion of a potential stratum but also of the entire reservoir and even of entirely separate prospects with similar geological features. Thus, there are many opportunities for an oil company, through its own information gathering procedures, to obtain information valuable to

others. In this respect, as one firm, X, has a commodity (information) which another firm, Y, values, there is the possibility of mutually beneficial exchange. However, oil field information often also has the property of "non-excludability" in which firm X is unable to prevent firm Y from sharing in the valuable information even if they do not agree upon terms of exchange.

Information is thus often an external good. For example, while a firm may be able to keep the results per se of a seismic survey private, if the firm acts upon the information in some particular way, say, by commencing drilling on a wildcat prospect, the firm may "tip off" others.³ Likewise, the results of completed test drilling may not easily be kept secret. It is typically observed that successful discoveries on one lease will drive up the value of surrounding acreage.⁴ This is an indication that the first discovering oil firm, if it does not already own all the relevant adjacent acreage, is giving away valuable information to others. In fact, one would expect that the mere initiation of drilling activity on land previously thought to be worthless would, by capitalizing the value of the expected future information, increase the value of the mineral rights of surrounding land. In these cases, surrounding lease owners are in the position of being "free riders" off the first person to begin drilling.

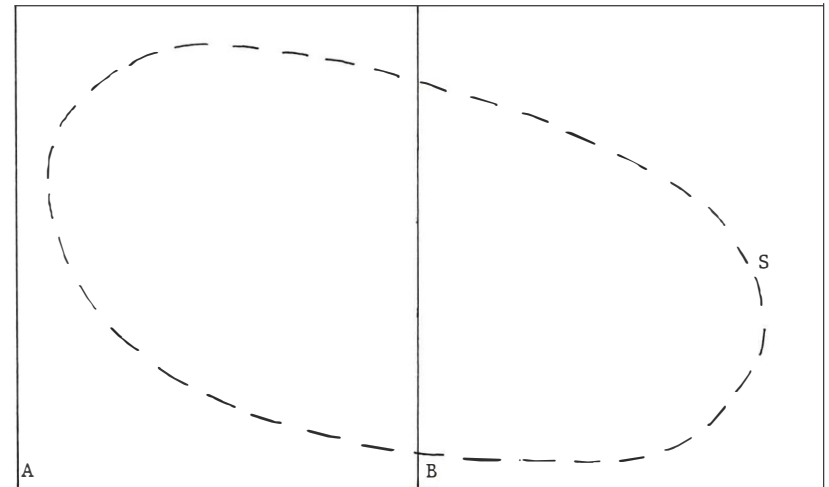
This paper is concerned with a special case of such information externalities, namely those in which there is more than one firm owning "informationally related" prospects and in which

each firm has the opportunity to be a free rider in receiving information paid for by another. A simple example is depicted in Figure 1. The dotted line indicates the boundaries of a geological formation. Firms A and B own or lease the mineral rights as depicted. Suppose that drilling a well on either property yields valuable information about both. Furthermore, suppose that the information obtained through drilling is not excludable, so A can gain information from drilling on B, and vice versa. If the external information flows are valuable, the model represents an interest conflict which I hope to model in the framework of game theory. This game theoretic model of two firms and "nature" is essentially the one employed by Stiglitz (1975).

Using this game theoretic model, it is easy to show that when the conflict takes the form of a noncooperative, nonconstant sum game, a suboptimal outcome can result. However, the more important part of this paper will be to examine the role of some "real world" institutions which Grayson calls "trading" arrangements (Grayson 1960). These institutions will be described in more detail in a later section, but the essential feature which will be modeled here is that they transform the noncooperative game, allowing it to be played as a cooperative game with side payments. In some instances, the existence of these trading arrangements allows the players to reach an optimal outcome.

In an earlier paper, which does not specifically consider the existence of these trading institutions, Peterson argues that the presence of information externalities in exploration suggests the need for government subsidies (Peterson 1975).⁵ A similar

FIGURE 1



argument was made by Stiglitz (1975). To the extent that cooperative information sharing institutions ameliorate effects of the externality, the need for government assistance is no longer indicated. However, it will be shown in this paper that the voluntary trading arrangements are not a cure-all. There are circumstances in which suboptimal results can still occur. This paper will attempt to distinguish the conditions in which the private trading institutions will fail from those in which they will be more successful. Particular attention will be paid to those cases in which all firms realize that they will be strictly better off by playing the game cooperatively. When this is true, the existence of trading agreements suggests that their evolution is a natural or expected institutional adaptation.

II. THE BASIC MODEL

Referring again to Figure 1, consider a tract of land under which there is a geological structure S . Suppose that the surface projection of S (represented by the dotted line) is divided in terms of ownership between two different tracts, one owned by firm A and the other by firm B. Because of this overlap, it will be assumed that the two tracts are informationally related⁶ and that each firm has precisely two ways of obtaining information about its own tract: i) drilling a wildcat exploration well whose information is nonexcludable, or ii) free-riding off of the information provided if the other firm drills a wildcat exploration well.

Such information overlaps are common in oilfield exploration. The problems caused by the resulting externality are well recog-

nized by oilmen. For example, John R. Kennedy (1976) remarks that "if we ignore the wildcat-contribution problem we invite either bankruptcy or the near termination of exploratory drilling" (p. 88). Grayson (1960) has described certain cooperative institutions, broadly called trading institutions, in which the value of the information externalities are specifically considered by the participants. Four commonly used institutions are:

- 1) the "dry hole contribution" in which firm X agrees to drill a well, and firm Y agrees to pay firm X money if the well turns out to be a dry hole.
- 2) the "bottom hole contribution" in which Y pays X regardless of the outcome of the well that X has agreed to drill.
- 3) the "acreage contribution" like 1) or 2), but acreage, rather than money, is exchanged.
- 4) the "joint venture" in which the firms combine their operations over the tracts.

It is of course clear that these institutions differ from one another in many ways, not the least of which is the manner in which they share their risks. For this paper, however, they will be collapsed into a general, abstract cooperative institution in which the firms agree to behave in a certain prescribed manner, and in which there may be an exchange of money between them. The question to be addressed is whether these cooperative institutions completely remedy any potential market failure caused by the externality.

The game form which will be used to model the firms' conflict will consist of two players (firms A and B) each with two strategies : i) drill an exploration well today (D); or ii) hold out until tomorrow (ND). The firms will be assumed to be expected profit maximizers. The "payoffs" of the games will be discounted expected profits. The normal form representation of the game is depicted in Figure 2. Relationships among the values of the entries in the payoff matrix will be set according to different axiom sets in order to create different games.

The payoffs to the firms are discounted expected profits. From the very beginning it has been posited that oil exploration is a risky undertaking. Implicit, then, in the 2 X 2 normal form representation of the games is an expanded game in which "nature" is a player via a random variable, Θ , which describes the presence or lack of oil. In this model, information about Θ comes only through drilling into the reservoir.

To illustrate the role of "nature's" play, consider the following example in which there are two states of the world: Θ_1 in which there is oil under both tracts and Θ_2 in which there is oil under neither tract.

Let: V_0^j be the discounted stream of earnings to firm j of a successful well drilled today.

V_1^j = the discounted stream of earnings to firm j of a successful well drilled tomorrow

C_0^j = the cost to firm j to drill a well today.

FIGURE 2

		D	B	ND
D		$E\bar{\Pi}_A(D,D); E\bar{\Pi}_B(D,D)$		
		$E\bar{\Pi}_A(D,ND); E\bar{\Pi}_B(D,ND)$		
A				
ND		$E\bar{\Pi}_A(ND,D); E\bar{\Pi}_B(ND,D)$		
		$E\bar{\Pi}_A(ND,ND); E\bar{\Pi}_B(ND,ND)$		

$E\bar{\Pi}_j(i,k)$ = optimal discounted expected profits of firm j when firm A uses strategy i and firm B uses strategy k.

C_1^j = the discounted cost to firm j of drilling a well tomorrow.

ϕ_1 = prob. of θ_1 , $(1 - \phi_1)$ = prob. of θ_2 .

Then, referring back to Figure 2, the optimal payoffs to firm A1 can be calculated as follows:

$$E\Pi_A(D,D) = E\Pi_A(D,ND) = \phi_1(V_0^A) - C_0^A$$

$$E\Pi_A(ND,D) = \phi_1(V_1^A - C_1^A) + (1 - \phi_1)(0) = \phi_1(V_1^A - C_1^A)$$

$$E\Pi_A(ND,ND) = \phi_1(V_1^A) - C_1^A$$

The structure of $E\Pi_A(ND,D)$ is important. By waiting until the other firm has drilled, firm A can avoid the cost C_1^A of drilling a structure known to be dry. The same relationship holds for firm B waiting until firm A has drilled.

Other more complicated models of uncertainty are possible (continuous outcomes, or the possibility that one well will be dry while the other procedures). The concept of the calculation of expected profits for each strategy choice remains the same.

Each of the noncooperative games will be considered in terms of existing solution concepts from the literature on game theory. It is hoped that this will capture the outcomes which a player (firm) would reasonably expect to occur if the games are

noncooperative. Then, this expected noncooperative outcome, a type of threat point, will be compared with the possible outcomes when the same games are played cooperatively, with side payments. When the analogous solution concepts, or "reasonable" outcomes, of the cooperative game present the opportunity for both players to have strictly higher payoffs than at the noncooperative outcome, then it is argued that the existence of these trading institutions is a natural response to the information externality.

Implicit in the consideration of the cooperative game is a "bargaining" process which allocates the surplus obtained from cooperative play. It will be assumed that the bargaining mechanism is taken as a given, and that all participants recognize that when there are gains from cooperation, the mechanism will make all players strictly better off.

III. THE NONCOOPERATIVE GAME

The general game form of the preceding section (see Figure 2) will be transformed into five specific games by choosing assumptions about the relationships among the payoff entries. However, throughout this section, the following assumptions will be maintained:

A1: The "game" does not continue after tomorrow. Both firms realize that if they both hold out (ND) until tomorrow, they will have to make their "drill/don't drill" decision based solely upon their own actions.

A2: Either well drilled individually today or tomorrow would earn nonnegative profits. If both firms hold out until tomorrow, the returns will be such that both firms decide to drill.

A3: If one firm drills today (D), its profits are unaffected by whether or not the other firm drills. This assumption requires that:

$$E\Pi_A(D,D) = E\Pi_A(D,ND) \quad \text{for firm A}$$

$$E\Pi_B(D,D) = E\Pi_B(ND,D) \quad \text{for firm B}$$

A4: Information is socially valuable in that the maximum of joint discounted expected profits occurs through sequential drilling (either (D,ND) or (ND,D)), and the information is privately valuable in that each firm would, if holding out, prefer to receive than not receive it.

That information is socially valuable can be seen to be a restriction on the relationship between revenues and costs in periods 0 and 1. The assumption requires that the maximum of discounted joint expected profits is either

$$\phi_1(V_0^A) - C_0^A + \phi_1(V_1^B - C_1^B) = (\text{A drills first and B observes } \theta):$$

or

$$\phi_1(V_0^B) - C_0^B + \phi_1(V_1^A - C_1^A) = (\text{B drills first and A observes } \theta).$$

Information is privately valuable in that

$$E\Pi_A(ND,D) > E\Pi_A(ND,ND); \quad \text{and}$$

$$E\Pi_B(D,ND) > E\Pi_B(ND,ND).$$

There are five two-person games, formed by assuming more structure on the relationship among payoffs, which are of particular interest. In analyzing these non-cooperative games, the solution concept which will be considered to be the "reasonable" outcome is the "solution in the weak sense" (Luce and Raiffa) (see discussion relevant to these specific games in Appendix I).

Game 1: HOLDOUT/HOLDOUT

Consider the following assumptions:

A5: Given that the other firm holds out, a firm is indifferent between drilling today and holding out until tomorrow, i.e.

$$E\Pi_A(D,ND) = E\Pi_A(ND,ND) \quad \text{or}$$

$$E\Pi_B(ND,D) = E\Pi_B(ND,ND)$$

A6: Given that the other firm drills, a firm would rather hold out and receive the information than drill.

$$E\Pi_A(ND,D) > E\Pi_A(D,D), \text{ or}$$

$$E\Pi_B(D,ND) > E\Pi_B(D,D)$$

The axiom structure [A1, A2, A3, A4, A5, A6] for both firms yields the normal form represented in Figure 3. Holding out (ND) is a dominant strategy for each firm, so (ND, ND) is a dominant strategy equilibrium. (ND, ND) is also the only strong Nash equilibria and the solution in the weak sense.

A similar result obtains if A5 is replaced by

A7: Given that the other firm holds out, the firm would rather hold out itself, i.e.

$$E\Pi_A(D,ND) < E\Pi_A(ND,ND) \text{ or}$$

$$E\Pi_B(ND,D) < E\Pi_B(ND,ND)$$

This may occur because the firm's development policy would require expensive "holding" of this resource if explored today, or because the firm is waiting for valuable information from another source.

FIGURE 3

GAME 1

		B		
		D	ND	
A	D	r,s	r,t	with t > s u > r
	ND	u,s	r,s	

EXAMPLE

		B		
		D	ND	
A	D	1,1	1,3	
	ND	2,1	1,1	

In the structure [A1, A2, A3, A4, A6, A7] for each firm, (call it game 1') (ND,ND) is the dominant strategy equilibrium, as well as the only Nash equilibrium and the solution in the weak sense. (See Figure 4). This is essentially the Siglitz (1975) game form.

GAME 2

Suppose the relationship between drilling today and drilling tomorrow when the other firm holds out is changed from A5 to A8:

A8: Given that the other firm doesn't drill, the firm prefers drilling today to drilling tomorrow i.e.

$$E\pi_A(D,ND) > E\pi_A(ND,ND)$$

$$E\pi_B(ND,D) > E\pi_B(ND,ND)$$

That is, absent the possibility of receiving a free good (information), the firm prefers to drill today. This could be due to costs of waiting such as lease payments, renegotiation deadlines, etc. However, when assumption A6 still holds, any waiting costs must be small enough so that the firm will still prefer to hold out if it knows that it will receive valuable information. If this modification holds for only one firm, while the other firm is described by A5 or A7, rather than A8, the axioms

FIGURE 4

GAME 1'

		B		
		D	ND	
A	D	r,s	r,t	t > q > s u > p > r
	ND	u,s	p,q	

EXAMPLE

		B	
		D	ND
A	D	1,1	1,5
	ND	3,1	2,2

firm is described by A5 or A7 rather than A8, the axioms [A1, A2, A3, A4, A5 or A7, A6] for A, and A[1, A2, A3, A4, A6, A8] for B result in a normal form game such as in Figure 5.

The choice facing firm B is now seemingly now more complicated. If A drills today, B would rather hold out; if A holds out, B would rather drill. However, a simple behavioral assumption is that firm A will never drill today, because A's dominant strategy is to hold out. Under the assumption that this is a game of complete information,⁷ B recognizes A's dominant strategy, and chooses his best response, D. Therefore, (ND,D) is the solution in the weak sense.

GAME 3: BATTLE OF THE SEXES

If A8, rather than A5, holds for each firm, the analysis becomes substantially more complicated. The general form is represented in Figure 6 along with a more illustrative numerical example.

Neither player has a dominant strategy. There are three Nash equilibrium points: (D, ND) and (ND, D) are strong Nash equilibria, and there is a weak Nash equilibrium in mixed strategies (in the example in Figure 6, the mixed strategy equilibrium is (probability of D = 1/2 probability of ND = 1/2) played by A and B).

Formally, because the Nash equilibrium pairs are neither equivalent nor interchangeable, this game is not solvable in any

FIGURE 5
GAME 2

		B		
		D	ND	
A	D	r,s	r,t	with $u > p \geq r$ $t > s$ $s > z$
	ND	u,s	r,z	

EXAMPLE

		B		
		D	ND	
A	D	1,1	1,1.4	
	ND	2,1	1, .4	

FIGURE 6

Game 3

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

with
 $r > w$
 $s > z$
 $t > s$
 $u > r$

Example

		B	
		D	ND
A	D	1,1	1,2
	ND	2,1	0,0

of the standard definitions. That the familiar concept of an equilibrium point fails to define a "reasonable" outcome can also be seen by a less formal analysis. Because the Nash equilibria are not equivalent, simply restricting attention to the set of equilibrium points does little to remove the element of conflict from the game. Firm A would strictly prefer to have the equilibrium (ND, D), while B would like (D, ND). Because the equilibria are not interchangeable, there is no guarantee that the players in the noncooperative setting can reach an equilibrium point even if they want to. Suppose A wants the equilibrium (ND, D), and so plays ND. If B wants the equilibrium (D, ND) and plays ND, the result is the outcome (ND, ND) which is not an equilibrium. In fact, by attempting to play either the mixed Nash equilibrium strategy or the favorable pure Nash equilibrium strategy, each firm faces the possibility (if the other firm plays something else) of receiving a lower payoff than by playing the maximin strategy which maximizes the minimum possible payoff (in the example game, that strategy is to drill today, for a "security level" of 1). In fact, the maximin strategy dominates the mixed equilibrium strategy. Of course, the disappointing truth is that the joint maximin outcome (D, D) is not in equilibrium.

There is one other possible way to describe the outcome of this noncooperative game. One can suppose that, given the absence of a well defined solution in the standard sense, each firm simply attempts to maximize its expected payoff based upon

some subjective probability distribution over the strategy choices by the other firm. We will return to the problems such a situation can cause in a later section.

GAME 4:

Finally, there is the possibility that for one firm A8 holds but not A6. Rather, the value of the drilling information to one firm is not enough to persuade it to hold out, even if it knows that the other firm intends to drill. This is expressed as A9^B.

$$A9: E\Pi_A(ND,D) \leq E\Pi_A(D,D) \text{ for firm A. or}$$

$$E\Pi_B(D,ND) \leq E\Pi_B(D,D) \text{ for firm B.}$$

If this is true for only one firm, say firm A, the result is as in Figure 7, represented by the axioms

For A: [A1, A2, A3, A4, A8, A9]

For B: [A1, A2, A3, A4, A6, and either A5, A7, or A8].

Firm A has a dominant strategy to drill today. Firm B, recognizing this, would hold off. This game is solvable in the weak sense at (D,ND).

VI. THE NONCOOPERATIVE GAMES AND THE QUESTION OF OPTIMALITY

In only one of the five games in the previous section will the socially optimal (in this case, joint profit maximizing) drilling pattern necessarily result. In games 1, and 1', a

FIGURE 7

GAME 4

		B		
		D	ND	
A	D	r,s	r,t	u < r
	ND	u,s	w,z	w < r
				s < t
				s ≥ z < t
				u > w

EXAMPLE

		B	
		D	ND
A	D	1,1	1,1.1
	ND	.9,1	.1,1.0

nonsequential drilling pattern (ND,ND) is the solution. In game 3 there is no solution, and no guarantee of the appropriate drilling strategy. In game 2, the result may not be optimal because the solution may be to drill the wells in the wrong order. For example, the firm which should efficiently "hold out" may face penalties on its lease if exploratory drilling has not commenced. The payoff matrix might look like Figure 8. In this example, the game is 2 with a solution (ND,D). However, the optimal staggered drilling order is (D,ND). Only in game 4 is the noncooperative play optimal. (A proof of this is shown in Appendix II.)

V. THE STRUCTURE OF COOPERATIVE DRILLING GAMES

Different of the four proposed cooperative arrangements may be appropriate under different circumstances. If the noncooperative result is that both firms hold out, a dry hole contribution, bottom hole contribution, or acreage contribution could induce one firm to drill. For the other cases, a joint venture or a combination of proposals might be suggested.

Yet the two critical characteristics of any cooperative play of the drilling game are that i) the firms are allowed the opportunity to communicate and coordinate their drilling strategy and ii) the firms can make "side payments" that is, transfers of cash or acreage.

The total net profit to each firm from a coordinated drilling strategy will be the profit from its own property plus

FIGURE 8

		B	
		D	ND
A	D	1.4, .9	1.4, 1.2
	ND	1.6, .9	1.4, .8

the net total of all side payments (which may be positive or negative).

Thus, there are two important choices to be made in the cooperative play of the game: i) the drilling strategies to be chosen, and ii) the side payments to be arranged.

The theory of cooperative game solutions is built upon two fundamental concepts: i) the coalition, and ii) the characteristic function. Let I be the set of all players. A coalition C is a subset of I which agrees to a joint strategy. The characteristic function of a game, call it $V(S)$, is a set function mapping subsets of I (coalitions) into the real numbers. The characteristic function denotes "the joint payoff which the members of any given coalition ($S \subseteq I$) would achieve if they did cooperate among themselves but did not cooperate with the remaining players" (Harsanyi, 1977, pp. 213). A characteristic function has the properties that $V(\emptyset) = 0$, and

$$V(R \cup S) \geq V(R) + V(S) \quad \forall R, S \subseteq I$$

(That is, two groups can always do at least as well by acting together as by acting separately.)

For the two person drilling games in this paper, the concern is with $V(A)$, $V(B)$, and $V(A + B)$. $V(A)$ and $V(B)$ are the payoffs each firm would get by acting alone. As has been shown in the previous section, however, this concept is neither simply nor unambiguously defined. Many game theorists have adopted the convention that $V(i)$ is person i 's maximin value,

that is, how much the one person coalition of i can guarantee if all other players (firms) turn against him. [See, for example, Von Neumann and Morgenstern (1953), pp. 538-564.] The question that needs to be asked here is how this general adoption of the maximin concept squares with some of the "reasonable" outcomes presented in the previous section. Unfortunately, all is not well as the following lemmata (about two person games) demonstrate:

Lemma 1: Let α^* be a dominant strategy for player j ; then, α^* is also a maximin strategy.

Proof: If α^* is not maximin \exists some strategy pair (α, β) such that $E\Pi_j(\alpha, \beta) > E\Pi_j(\alpha^*, \beta) \leftrightarrow$.

Lemma 2: Let (α^*, β^*) be a dominant strategy equilibrium. Then, for each player j , $E\Pi_j(\alpha^*, \beta^*) \geq \hat{V}(j)$ if $\hat{V}(j)$ is the maximin characteristic function.

Proof: If, say, $\hat{V}(A) > E\Pi_A(\alpha^*, \beta^*)$ then \exists a strategy α such that $E\Pi_A(\alpha, \beta^*) > E\Pi_A(\alpha^*, \beta^*) \leftrightarrow$.

Lemma 3: Let (α^*, β^*) and $\hat{V}(j)$ be defined as in Lemma 2. It can be true that for both players, $E\Pi_j(\alpha^*, \beta^*) > \hat{V}(j)$

Proof: Consider

		D	B	ND
A	D	10, 10	4, 2	
	ND	2, 4	2, 2	

$$V(A) = V(B) = 4$$

$$\alpha^* = D, \beta^* = D$$

$$E\Pi_A(D,D) = E\Pi_B(D,D) = 10$$

Lemma 4: If A has a dominant strategy α^* , and $\hat{\beta}$ is B's "best response," $\hat{\beta}$ need not be B's maximin strategy.

Proof: Consider

		D	B	ND
A	D	100, 10	100, 4	
	ND	4, 0	4, 4	

$\alpha^* = D, \beta = D,$
but B's maximin strategy is ND.

Lemma 5: If the pair (α', β') is the "solution in the weak sense," $E\Pi_j(\alpha', \beta') \geq \hat{V}(j) \forall j$ where $\hat{V}(j)$ is the maximin value.

Proof: Suppose $\hat{V}(A) > E\Pi_A(\alpha', \beta')$. Then, $\exists \alpha \ni E\Pi_A(\alpha, \beta') < E\Pi_A(\alpha', \beta')$. But, then, (α', β') is not an equilibrium in the reduced game \rightarrow .

Lemma 6: Let $\alpha', \beta',$ & $\hat{V}(j)$ be defined in Lemma 5, then it is possible that for both players $E\Pi_j(\alpha', \beta') > \hat{V}(j)$

Proof: Consider

		D	B	ND
A	D	100, 5	80, 4	
	ND	4, 0	4, 4	

(D,D) is the solution in the weak sense.
 $\hat{V}(A) = 80 < E\Pi_A(D,D) = 100$
 $\hat{V}(B) = 4 < E\Pi_B(D,D) = 5$

All of the games developed in the previous section, except G3, have either dominant strategy equilibria or solutions in the weak sense (a dominant strategy equilibrium is also a solution in the weak sense). The maintained behavioral proposition of this paper is that if both players see that the cooperative play makes them better off, then the cooperative institutions are a "natural response."

However, this leaves a key conjectural ambiguity. How does player A believe that player B will respond? In the context simply of noncooperative play, the reasoning behind solutions such as the solution in the weak sense suggests that if firm A has a dominant strategy, firm B recognizes this, and (despite any preplay threats) B believes A will ultimately choose to play his own dominant strategy. As was previously mentioned, however, when dealing with cooperative games, the reasoning typically begins with the concept of the best someone can do if everyone else turns against him.

As was demonstrated in Lemma 5, the divergence between the maximin characteristic function and the weak solution is asymmetric. The payoff at the solution in the weak sense is always at least as great as the maximin characteristic function. This is intuitive. No player will ever consider a "reasonable" outcome one which pays less than the same player would guarantee himself regardless of the outcome of others. However, as shown in Lemma 6, there is the possibility that the outcome at the solution in the weak sense pays each player more than the maximin characteristic function value.

The problem for this analysis is that by underevaluating $V(i)$, one runs the risk of overstating the potential for cooperative play. Therefore, the following alternate characteristic function, $V^\circ(S)$, for games with a solution in the weak sense, is proposed:

$$\bullet V^\circ(\Phi) = 0$$

$$\bullet V^\circ(j) = E\Pi_j(\hat{\alpha}, \hat{\beta}) \text{ where } (\hat{\alpha}, \hat{\beta}) \text{ is the solution in the weak sense of the noncooperative game, } (j = A, B).$$

$$\bullet V^\circ(A \cup B) = \text{the maximum of joint profits obtained from an efficient drilling schedule.}$$

(Note that $V^\circ(S)$ fulfills the conditions that

$$V^\circ(\Phi) = 0$$

$$V^\circ(R \cup S) \geq V^\circ(R) + V^\circ(S) \quad \forall S \subseteq I).$$

In terms of the drilling games developed in the previous section, the potential for cooperative institutions occurs when each firm sees itself being better off at the outcome of cooperative play than at the "reasonable outcome" of noncooperative play. In the setting of cooperative games, the first criterion which will be adopted for a "reasonable" outcome is that it is in the "core." That is, let $X = (E\Pi_A^*, E\Pi_B^*)$ be a vector of final net expected profits to the firms. X is in the core if

$$i) \quad E\Pi_A^* + E\Pi_B^* = V(A \cup B)$$

$$ii) \quad E\Pi_A^* \geq V^\circ(A)$$

$$.ii) \quad E\Pi_B^* \geq V^\circ(B)$$

The previously developed restriction on the definition of the bargaining mechanism can be formally stated as a second criterion on a proposed outcome X .

$$\text{If} \quad X = (\Pi_A^*, \Pi_B^*) \text{ and}$$

$$\Pi_A^* + \Pi_B^* > V^\circ(A) + V^\circ(B)$$

$$\text{then} \quad \Pi_A^* > V^\circ(A); \quad \Pi_B^* > V^\circ(B)$$

That is, both firms will be made strictly better off when cooperative play procedures greater joint expected profits than noncooperative play. Other "fair" properties of bargaining mechanisms are discussed in Harsanyi and Luce and Raiffa. A specific example of a bargaining scheme is given by Kennedy.

Because of the implicit bargaining procedure, the possibility of an extended bargaining game (see Luce and Raiffa pp. 140-143) must be addressed. In an extended bargaining game, the firms would list moves in the noncooperative game as binding threats, say d_A and d_B . Then the outcome (d_A, d_B) would become the threat point for the bargaining mechanism. In Harsanyi's terms, the noncooperative threat game becomes "dependent" on the bargaining game. However, it will be assumed here that firms cannot make binding threats. In Harsanyi's terms, the noncooperative conflict game is "independent" of the bargaining game. The "threat point" or expected outcome will be determined strictly by the noncooperative play as outlined in the previous section, and not by any preplay nonbinding threats made by the firms.⁹ So, for games 1, 1', 2, and 4 the "solution in the weak sense" will still be considered the expected noncooperative outcome.

In the four games with a weak solution in noncooperative play, the important policy conclusion is that the incentives for joint action ($V^o(A \cup B) > V^o(A) + V^o(B)$) occur precisely when the expected result of noncooperative play is inefficient. Furthermore, when this occurs, there is some

outcome in the core (chosen by a bargaining mechanism) that makes both firms strictly better off than noncooperative play. If activating these institutions is costless, then the existence of the information externality is not per se an argument for an exploration subsidy in these cases.

When the maximin characteristic function, call it $V(S)$, is used, this implication runs only in one direction. When the solution is nonoptimal, firms recognize the gains from joint action. However, in game 4, Figure 7, (D,ND) is the solution in the weak sense but $\hat{V}(A \cup B) > \hat{V}(A) + \hat{V}(B)$.

However, there is still the case of game 3. It is quite possible that no reasonable characteristic function exists for this game. In the example in Figure 6, the maximin outcome is (D,D) with a payoff (1,1). If each firm views its maximin value as the "threat point" payoff, $\hat{V}(j)$, then each firm will recognize the potential gains from cooperative play, as $\hat{V}(A \cup B) > \hat{V}(A) + \hat{V}(B)$. But (D,D) is not an equilibrium, and it is not unreasonable to suspect that there are conditions in which one expects a greater payoff. However, suppose we create a function $V'(j)$ which is the amount j "expects" to receive from noncooperative play (with j 's expectation based upon his own subjective evaluation of his opponents strategy). There is always the possibility that each firm is (incorrectly) convinced that it can bluff out the other; each plays the strategy ND, and $V'(A) + V'(B) = (2) + (2) > V(A \cup B)$ (the efficient outcome). Neither firm would initiate cooperative play, and a promoter attempting to put together a deal would be frustrated by the

firms' attitudes. In such a situation, noncooperative play leads to a suboptimal result, but private cooperative action would fail.

VI. SPECIAL CONSIDERATIONS

As is to be expected, "real world" circumstances diverge from the assumptions of the model in a way which requires some special attention.

First, it has been assumed that activating the cooperative institutions is costless. If it is not, then voluntary cooperation may fail even when these models indicate that it would succeed. The problem of institutional cost is undoubtedly exacerbated as the number of firms goes from 2 to N . Locating lease owners, coordinating the discussions, etc. becomes more costly. Furthermore, the game analysis becomes more complicated as firms have the opportunity to be "free riders" off of the drilling negotiations of others. For example, firms Z and W want Y to pay X to drill, etc. A classic public goods problem results if no firm views its own increase in expected profits from going along with the promoter's deal as being greater than its costs in the deal. This "public goods" problem suggests that the presumption for public intervention is greater as lease ownership patterns are more fragmented.

On the other hand, there is another factor which may make voluntary contributions more attractive than presented in this paper. It may be the case that the information externality is very imperfect; that is, the "free rider" firm gets some

information, but not as much as from actually drilling the well. The legal contract for cooperative ventures typically specifies that all pertinent information (drilling logs, electrical logs, drill stem tests, drilling core results, etc.) must be given to all parties. If such detailed information is sufficiently more valuable than "free rider" information, a promoter may convince both firms in game 3 that cooperation is profitable, or provide an extra incentive to firms in the N firm case to be participants in the venture.

VII. SUBSIDIES AND MARKET FAILURE

Several cases have been identified in which the potential for market failure is present even when the possibility of a cooperative exchange institution is allowed. Therefore, the concerns raised by Peterson and Stiglitz are still valid. Among the nonmarket solutions suggested by each is a program of government subsidies for exploration. However, the model developed here can be used to show that some subsidy schemes can make matters worse.

Consider the "battle-of-the-sexes" drilling game, game 3, as depicted in Figure 8. There exists a subsidy scheme for which an optimal drilling strategy obtains and for which the increase in profits is greater than the cost of the subsidy. This is achieved by paying either A or B a $\$(1 + \epsilon)$ subsidy for drilling today, and informing the other firm so that it may hold out. However, the subsidy must be selective. If a general blanket subsidy program of $\$(1 + \epsilon)$ is adopted, both firms drill today, and a suboptimal result (D,D) obtains. In fact, the gain in total profits is less

than the final cost of the subsidy. Furthermore, a general subsidy could make matters worse if it interfered in the operation of the private cooperative agreements in those situations in which the private agreements are effective. The key point is that market failure does not arise merely from too little drilling today: it may also derive from improperly sequenced drilling.

Unfortunately, the information requirements for the appropriate selective subsidy are tremendous. As Stiglitz (1975, p. 94) suggests, there are other approaches which should be considered. Among the possibilities are imposed joint venture exploration with a single operator, some variant of an "incentive compatible" system for providing public goods, or changes in leasing policy.

VIII. CONCLUSION

Recommending public subsidies for oil exploration based on information externalities overlooks the existence of private cooperative institutions designed to facilitate cooperative drilling strategies. It was shown that under several reasonable conditions, private cooperative institutions are a natural result of the derived two-person drilling game. However, there are other situations in which there is no guarantee that suboptimal non-cooperative behavior will induce firms to efficient drilling patterns. This occurs when the drilling game is of the "battle-of-the-sexes" type. The appropriate selective subsidy would be an appropriate remedy in this case. A general subsidy could improve results or make matters worse.

As the number of firms goes from 2 to N, the costs of organizing increase, and additional free rider problems arise. However, it may also be the case that participation in cooperative drilling provides the firm with "better" information than from being a free rider. The first of these modifications makes cooperative less likely to succeed; the second improves the prospects for an optimal agreement.

APPENDIX I

The solution concept adopted here is the "solution in the weak sense" of Luce and Raiffa (pp. 106-109). For the two-person, two-pair strategy games of this paper, it is important to note the following:

- 1) A dominant strategy equilibrium is a solution in the weak sense (it is the only strategy in the reduced games, so it is trivially an interchangeable, equivalent equilibrium in admissible pairs, thus a solution in the strict sense of the reduced game).
- 2) When one firm plays a dominant strategy, α' , and the other firm plays a best response, β' , the pair (α', β') is the solution in the weak sense. (Again, trivially, (α', β') is admissible in the reduced game, and it is the only equilibrium in the reduced game.)

Dominance in this paper is used in the following sense:

α dominates α' if and only if

$$[E\pi_j(\alpha, \beta') \geq E\pi_j(\alpha', \beta')] \quad \forall \beta'$$

with $>$ holding for at least one β' . α is a dominant strategy if it dominates all other strategies.

APPENDIX II

Lemma: The solution in the "weak sense" of game 4 is the social optimum

Proof: Game 4 is

		B		
		D	ND	
A	D	r,s	r,t	u < r
	ND	u,s	w,z	w < r
				u > w
				s < t
				s > z < t

The solution is (D,ND).

$t > s$ so (D,D) cannot be an optimum. Likewise $r > u$ rules out (ND,D). Finally $r > w$, $t > z$ eliminates (ND,ND).

FOOTNOTES

1. When production decisions must be made ex ante, information can be used to improve production choices in a way which increases expected profits. (See Hirshleifer, 1971).
2. In fact, the complete profile of the structure may not be known until the entire production history of the well is complete, if then. But, Kennedy (1976) says, "Any wildcat has some value.... At the very worst, they establish that yes, the granite is indeed only 300 ft. below the surface, and everybody can now drop their acreage in the area and get on with better things. At the very best, a significant new discovery is made, and everybody can now start hustling for rigs and tubular goods."
3. See especially Arrow (1974).
4. Peterson (1975) gives an example from the Alaska North Slope.
5. In a later paper, Peterson (1978) mentions these institutions in a footnote, but does not incorporate them in his analysis.

6. This paper will not consider the more general topic of production externalities between the properties.
7. "Complete" information is defined here to mean that each player knows the strategies and associated payoffs available to the other players.
8. Given A3 and A4, if A5 or A7 holds rather than A8, A9 cannot hold. To see this, consider A's payoffs

		B	
		D	ND
A	D	r	r
	ND	u	w

A5 or A7 $\Rightarrow w \geq r$.

A4 $\Rightarrow u > w$

$\Rightarrow u > r$ which contradicts A9.

It is also true that given A3, if A9 holds for both firms, then A4 cannot hold. Consider

		B	
		D	ND
A	D	r,s	r,t
	ND	u,s	w,z

By A9 $r \geq u$, $s \geq t$. By A4 (the second part) $u > w$, $t > z$ and (D,D) is the social maximum \leftrightarrow .

9. Kennedy relates that the principal difficulties he has experienced in dry hole contribution bargaining were:
- "1. Operators proposing a test will have generally tried to argue a gross exaggeration of the value of the test to owners of surrounding acreage, while at the same time pretending to ignore its value for their own acreage in the area outside the drilling unit.
2. Nonoperator acreage owners around the proposed test have carried on a similar charade, pretending to virtual indifference as to whether the well is drilled, yet perversely insisting on its great value to acreage owners in the drill site unit."

Kennedy's article is, in fact an exposition of a particular bargaining mechanism, based on distance from the drill site.

REFERENCES

- Arrow, Kenneth J. "Economic Welfare and the Allocation of Resources for Invention." In Essays on the Theory of Risk Bearing. New York: American Elsevier Publishing, 1974.
- Grayson, C. Jackson. Decisions Under Uncertainty: Drilling Decisions by Oil and Gas Operators. Boston: Harvard University Graduate School of Business Administration, Division of Research 1960.
- Harsanyi, John C. Rational Behavior and Bargaining Equilibrium in Games and Social Structures. New York: Cambridge University Press, 1977.
- Hirshleifer, Jack. "The Private and Social Value of Information and the Reward to Inventive Activity." American Economic Review 61 (1971):561-575.
- Kennedy, John R. "A Look at Dry-Hole Contributions." Oil and Gas Journal 74 (1976):88-91.
- Luce, R. D. and Raiffa, H. Games and Decisions. New York: John Wiley & Sons, 1957.
- Peterson, Frederick M. "Two Externalities in Petroleum Exploration." In Studies in Energy Tax Policy. Cambridge, Mass: Ballinger Publishing Co., 1975.

Peterson, Frederick M. "A Model of Mining and Exploring for Exhaustible Resources." Journal of Environmental Economics and Management 5 (1978):236-251.

Stiglitz, Joseph E. "The Efficiency of Market Prices in Long Run Allocations in the Oil Industry." In Studies in Energy Tax Policy. Cambridge, Mass.: Ballinger Publishing Co., 1975.

VonNeumann, John and Morgenstern, Oskar. Theory of Games and Economic Behavior. 3d ed. New York: John Wiley and Sons, Inc., 1953.