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Game Theory

Mediated Talk

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Abstract: The notion of mediated talk in which players communicate through a mediator before starting the game is introduced. It is shown that a deterministic mechanized mediator receiving private inputs and producing public outputs can generate any rational correlated equilibrium with rational probabilities by a self-enforcing procedure.

1 Introduction

In correlated equilibrium (Aumann, 1974, 1987), players are endowed with private information before starting the game. The actions taken depend on this private information, which is usually correlated across players. Therefore, correlated equilibrium describes a situation where players start the game with previous records. For instance, a player may have observed previous public signals like various market prices or sunspots, or other sorts of information like the player's own previous decisions in other situations. These observations may be helpful in newly encountered interactions, and players may rely on them before making a new decision. Since players' knowledge partially consists of public domain and partially of private domain, different players possess correlated information structures.

Sometimes players may want to generate artificially correlated private information among players. This may happen in at least two scenarios. In the first one, correlated equilibrium may provide payoffs, which Pareto dominate any Nash equilibrium payoff. In this case, players may agree on some mediation device which induces the desired correlation.

In the second scenario, a subset of players may want to deter another player from deviating. The deterrence is accomplished by a threat that can be carried out only by an external mediation device. When a subgroup of players is correlated, it can be considered as one player who can punish more effectively a deviating player. The option of more effective punishment usually implies a greater set of

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sustainable payoffs, some of which are favorable to the players who resort to the mediation device.

One way of generating correlation is to have a reliable person who will utilize a certain lottery and provide the players with private information that depends on the lottery outcome. The flaw of this option, though, is that it is not immunized against espionage or bribery. A player who knows more than he should may take advantage of it and gain at the expense of others. Moreover, a biased mediator might alter the lottery used in favor of some players.

Another way of generating a deviation-free correlation device was suggested by Barany (1992). In this scheme, players randomly choose elements in a certain set and then send partial information to prespecified peers. Players then send and receive information back and forth. Some messages are supposed to be sent by two players and then checked. This design deters players from unilateral deviation; in case of inconsistent messages, the deviating player can be identified and punished. Barany's result holds for a set of at least four players, and in order to induce it there must be a punishment phase, which prevents the procedure from being a subgame perfect equilibrium (in the entire game, including the communication phase).

In this paper we introduce a mechanical correlation. Players will send random inputs and receive outputs. The combination of input–output will induce a correlation among players. Before agreeing on the mechanism, players may want to know all the features of it. In particular, they may want to know the algorithm by which the machine generates lotteries, if it does so. However, if the inputs are public and the algorithm is known, each player can emulate the machine and produce its output, which is not random anymore. Moreover, a known machine with public inputs cannot generate private information.

All of the above attests to the fact that a machine that serves as a correlation device must receive private inputs. Indeed, the machine proposed here receives private inputs and it is the simplest of its sort. First, this machine does not use lotteries. The randomness is generated solely by players. It produces a deterministic output as a function of the received inputs. Second, the machine output is public: it can be a radio broadcast.

The machine provides a means by which players talk. The players send messages to the machine in order to receive outputs. We therefore call it a *mediated talk*. The mediated talk is taking place before the game starts and it serves as a coordination/correlation device. In order to induce an equilibrium, the mediated talk is designed in such a way that no player can gain by unilaterally deviating from the prescribed procedure.

The machine suggested here has two additional features: it may serve as a correlation device in case of two players or more, and it is also espionage free. For an outside party, even if, as a result of espionage, for instance, the machine structure becomes known, no gain can be derived from it. That is, the knowledge about the machine and its output can give no advantage to an outside party without knowing the private inputs sent. This is very important when the outside party is supposed to be punished by correlated players.

It may seem at first glance that a punishment executed by correlated players poses only a problem of coordination and not of keeping secrets from one another. In the context of repeated games, however, when a punishment is in order, one may want to resort to a deviation free mechanism in order to establish, for instance, a subgame perfect equilibrium. Thus, in such a case, the mediated talk serves not only as a simple mediating device but also as a self-enforcing procedure.

The correlation mechanism can obviously be used by two remote agents of the same player. For instance, two remote divisions of the same corp can be correlated by espionage free public radio broadcasting. Two remote agents can transmit private inputs to the machine. In turn, the machine produces an output that is made public by a radio, for instance. Then each agent takes an action which is a function of his private input and the public signal. In this case the mediated talk serves only as a public communication which is encoded by each player using his own private signal as a code. The possibility of deviation is not an issue here.

Another motivation for the study of a public mediator is that public signals observable by all agents are very common. Economic agents, for instance, may condition their decisions upon previous market prices, which are commonly known. Thus, agents' own actions and public prices serve as a mediating means. Also, the government can serve as a public mediator. Citizens send private signals (e.g. by their tax returns). In turn, the government produces a public output (e.g. an economic policy or even a simple public announcement). Both constitute a mediating device, where the government serves as the channel through which citizens communicate. In other words, the citizens talk using the public mediation of the government.

It is obvious that market prices and tax returns have direct payoff consequences and do not serve primarily as a means of mediation. Still, the question naturally arises as to what are the correlations that arise from public mediated talks.

The result of this paper is that, by mediated talk that produces public outputs, any correlted equilibrium with rational entries can be generated. Moreover, the mechanism is self-enforcing.

This work pertains to two branches of the literature. It relates on one hand to works of Forges (1986, 1990), and Myerson (1982, 1992), which deal with correlation in various instances of Bayesian games, and to Lehrer (1992), which treats correlation through private histories in long games. On the other hand, it relates to papers written on the subject of cheap talk, frequently associated with sender–receiver games. See, for instance, Crawford and Sobel (1982), Farrell (1993). Aumann and Hart (1992) presented a type of pre-play communication called polite talk in games of complete and incomplete information. In their polite talk, every player talks in his turn. The talk may be infinitely long or finite and the messages of each player become public. It turns out that, in a complete information game, the convex hull of the Nash equilibrium payoffs set can be generated. In games with incomplete information where the lack of information is on one side, Aumann and Hart get an expanded equilibrium payoff set characterized in terms of bi-martingales (see Hart (1985)).

Contrary to some papers mentioned, here the talk that takes place before playing is not meant to share private information that some players might have been endowed with, but rather to generate private information. Mediated talk that serves both purposes, sharing and creating private information, is yet to be dealt with.

2 An Example

Suppose that the game played is the game of the chicken:

	l	r
t	6,6	2,7
b	7,2	0,0

It is well known that the correlation

$P_1 =$

1/3	1/3
1/3	0

provides the player with the payoff (5, 5). This payoff lies outside the convex hull of the Nash equilibrium payoffs. The correlation

$P_2 =$

1/2	1/4
1/4	0

sustains the payoff $(5\frac{1}{4}, 5\frac{1}{4})$, which is also outside the convex hull of the Nash equilibrium payoffs. It turns out that the idea of generating these two correlations and any other 2×2 correlation passes through the uniform distribution over the cells of the 2×2 matrix.

The first step is to construct an input–output deterministic machine which generates the correlation

$U =$

1/4	1/4
1/4	1/4

with the additional features that no player can unilaterally alter the desired distribution. In this step we ignore the payoff matrix and consider only distributions over the matrix cells.

Let us look at the following 4×4 matrix.

$$S = \begin{array}{c|cccc|} & 1 & 2 & 3 & 4 \\ \hline 1 & a & a & c & c \\ 2 & a & a & c & c \\ 3 & c & c & a & a \\ 4 & c & c & a & a \end{array}$$

The matrix $S = (s_{ij})$ describes the machine that produces the public outcome s_{ij} when player I sends the message i and player II sends the message j. Suppose now that each player selects a message from the set $\{1, 2, 3, 4\}$ with probability $1/4$ each. Then each player receives the public output and follow the strategy described as follows

Table 1. Strategy of Player I

Input and Output		Corresponds to
1	*a*	*t*
2	*a*	*b*
1	*c*	*b*
2	*c*	*t*
3	*a*	*b*
4	*a*	*t*
3	*c*	*t*
4	*c*	*b*

Table 2. Strategy of Player II

Input and Output		Corresponds to
1	*a*	*l*
2	*a*	*r*
1	*c*	*r*
2	*c*	*l*
3	*a*	*r*
4	*a*	*l*
3	*c*	*l*
4	*c*	*r*

A direct computation reveals that, if both players follow the strategies and play the action corresponding to their private input and to the public output, the distribution induced is indeed the uniform distribution U.

Moreover, any change of *one player* in the distribution by which he selects his private input will not affect the correlation and it will remain U, as long as the players follow the strategies indicated in Tables 1 and 2.

In the second step of the construction we inflate the matrix S by replacing its entries with matrices of a fixed size, which depends on the desired correlation. In the case of P_1, for instance, the size of the replacing matrix is 1×1; we replace the entries corresponding (with respect to the strategies in Tables 1 and 2) to (b, r) by $*$ and keep all the rest unchanged. The result of this alternation is

$$S' = \begin{pmatrix} a & a & c & * \\ a & * & c & c \\ c & c & * & a \\ * & c & a & a \end{pmatrix}.$$

The strategies of players I and II are those indicated in Tables 1 and 2 with the change that $*$ means: "start the process all over again until you hit a signal different from *."

To summarize, each player selects, as an input, an element of the set $\{1, 2, 3, 4\}$ with equal probability and secretly transmits it to the machine. The machine then produces an outcome which is made public. If the outcome is $*$, the players try again. If on the other hand, the outcome is a letter, they follow Tables 1 and 2 and play the original game.

Two points should be noticed: (a) At the mediation phase, no player can unilaterally affect the distribution over the action combinations. (b) Since P_1 induces a correlated equilibrium, there is no incentive to deviate from the strategies prescribed. We therefore conclude that the machine described in S' together with the strategies mentioned generate P_1.

In order to generate P_2, we inflate S in a different way. Now we replace the entries of S with matrices of the size 2×2.

Any entry x in S, corresponding to (b, l) or to (t, r), is replaced by $\begin{pmatrix} x & * \\ * & x \end{pmatrix}$. Any entry corresponding to (t, l) is substituted by $\begin{pmatrix} x & x \\ x & x \end{pmatrix}$ and all other entries are replaced by $\begin{pmatrix} * & * \\ * & * \end{pmatrix}$. The resulting matrix is an 8×8 matrix S'':

$$S'' = \begin{pmatrix} a & a & a & * & c & * & * & * \\ a & a & * & a & * & c & * & * \\ a & * & * & * & c & c & c & * \\ * & a & * & * & c & c & * & c \\ c & * & c & c & * & * & a & * \\ * & c & c & c & * & * & * & a \\ * & * & c & * & a & * & a & a \\ * & * & * & c & * & a & a & a \end{pmatrix}$$

In S'' each player has eight possible inputs: $\{11, 12, 21, 22, 31, 32, 41, 42\}$. The output depends on the inputs in the obvious way. For instance, if the inputs of players I and II are 11 and 22, respectively, then the output is *. The meaning of * is always "start over". If the signal is a letter, then the players should follow the strategies described in Tables 1 and 2, where the second digit of the selected input is ignored. For instance, if player I's input is 21 and the output is c (which may be the case if Player II's input is either 31, 32, or 42), the action taken is t. This is because, according to Table 1, t is the action corresponding to input 2 and output c. The second digit of 21 is ignored and only the first one, 2, is considered.

A direct computation shows that the weight of all the entries corresponding to (t, l) are doubled, while the weight of those corresponding to (b, r) become zero. Thus, the generated correlation is indeed P_2. This mechanism induces a correlated equilibrium because no player can affect the distribution over action combinations, given that the strategies prescribed are played, and, moreover, that these strategies are best responses.

3 The Model

In this section we introduce the model of mediated talk and then show how it applies to examples of the previous section.

Let G be an n-player normal form game, where A_j is player j's set of actions. Set $A = \times A_j$. A *mediated talk*, D, is the procedure described by:

1. I_j, a finite set of player j's *inputs*, $j = 1, \ldots, n$.
2. M_j, a finite set of player j's messages (outputs), $j = 1, \ldots, n$. Each M_j is divided into two sets: L_j and K_j. When player j receives a message in L_j, he knows that it is time to play (to take an action in A_j). In case the message is in K_j, he knows that the conversion must go on, as will be described later.
3. An *output function*, $T: I_j \to \times M_j$, then attaches to any input combination a vector of outputs. T_j is the projection to M_j. Thus if $(i_1, \ldots, i_n)$ is the joint input, $T_j(i_1, \ldots, i_n)$ is the message given to player j. T has the property that, for any j, if $T_j(i_1, \ldots, i_n) \in L_j$, then for all other players j', $T_{j'}(i_1, \ldots, i_n) \in L_{j'}$. That is, if player j is informed to play, all other players are also informed so.
4. A *conversation policy* (or *communication policy*) g_j for every j. g_j specified the way player j should select an input in I_j after any history of inputs–outputs, $(i_j^1, k_j^1, i_j^2, k_j^2, \ldots, i_j^t, k_j^t) \in (I_j \times K_j)^t$, $t = 1, 2, \ldots$. The history of inputs–outputs consists of the input of the first stage of the talk, i_j^1 and of the message given to player i at this stage, k_j^1. It also consists of the input–output pair of the second stage, i_j^2 and k_j^2, and so on. Notice that all the messages (outputs) are in K_j, which means that the conversation must continue.

A history of inputs and outputs is called a *conversation history*. A *public mediated talk* is a mediated talk where $T_1 = T_j$ for every j. Thus, all the messages coincide.

Remark: The conversation policy of g_j can be random; it may prescribe a random selection of inputs after every conversation history.

We require that every history will terminate with a message from L_j with probability 1. That is, the conversation is finite with probability 1.

A *strategy* of player j, f_j, prescribes an action to every history of inputs–outputs that terminates with an output in L_j. Specifically, let h be a history in $(I_j \times K_j)^t \times (I_j \times L_j)$, $t = 0, 1, \ldots, f_j(h)$ is an action in A_j.

Certainly any mediated talk D and a joint strategy $f = (f_1, \ldots, f_n)$ induce a distribution over A, the set of joint actions in G. If this distribution is a correlated equilibrium and, moreover, if the procedure is self-enforcing, we say that D and f induce a correlated equilibrium.

Before we proceed to the main result, let us see how the model applies to the example of generating the distribution $\begin{pmatrix} 1/3 & 1/3 \\ 1/3 & 0 \end{pmatrix}$. Recall the 4×4 matrix S'. Here the input sets, I_1 and I_2, were $\{1, 2, 3, 4\}$. The messages players received were either a letter (a or b) or *. So the output function T is described by the matrix S'. The output a or b meant that an action should be taken. Thus, $L_1 = L_2 = \{a, b\}$. The output * meant that the conversation must continue. Thus, $K_1 = K_2 = \{*\}$. The conversation policies were always to choose an input from I_j with equal probability (after *every* history in $(I_j \times K_j)^t$).

Recall the strategies indicated in Tables 1 and 2 of the previous section and notice that the action taken depends only on the last pair of input–output and not on the entire conversation history.

4 The Result

Theorem: Let P be a distribution over A which induces a correlated equilibrium. Suppose that P assigns every joint action in A a rational probability. Then, there exist a mediated talk D and a joint strategy f that together induce the correlated equilibrium P.

Proof: Without loss of generality, we may assume that each player has the same number of actions. If not, one can replicate some actions as many times as needed. Suppose that $A_j = \{0, \ldots, s-1\}$ for every j.

The construction proceeds in two stages. We first define an auxiliary mediated talk, D'. All of its components are denoted with prime.

Set $I'_j = \{0, \ldots, s-1\}^2$. Thus, the inputs from I'_j consists of pairs of whole numbers between 0 and $s-1$. Suppose that the joint input is $i = (i_1^1, i_2^1, i_1^2, i_2^2, \ldots, i_1^n, i_2^n)$, where (i_1^j, i_2^j) is the input of player j. Define, for every j, $T'_j(i) = (\sum_{j=1}^n i_1^j)(\mathrm{mod}\, s)$. Thus, the output T'_j is also in the set $M'_j = \{0, \ldots, s-1\}$. Set $L'_j = M'_j$, which means that the play starts immediately after receiving the first output. Therefore, the conversation phase consists of one stage of communication only. Define g'_j, the conversation policy, to be: choose one pair in the set $\{0,\ldots,s-1\}^2$ with uniform distribution and send it as an input.

Suppose now that the output is s'. Define $f'_j(i_1^j, i_2^j, s') = (i_2^j + s')(\text{mod}\, s)$. f'_j prescribes an action in A_j. Notice that only the first component of player j's input, i_1^j, plays a role in determining the output, s', while i_2^j, the second component, plays a role only in defining the action.

Given the joint strategy $f' = (f'_1, f'_2, \ldots, f'_n)$ and $g'_{-j} = (g'_1, \ldots, g'_{j-1}, g'_{j+1}, \ldots, g'_n)$, any other communication policy, g''_j, of player j cannot affect distribution over A. This is for two reasons.

a. The distribution over M_j given any pair (i_1^j, i_2^j) is uniform. That is, assuming g_{-j} and given any input, the output is uniformly distributed over M_j. This is so because whenever all the input $i_1^1, i_1^2, \ldots, i_1^{j-1}, i_1^{j+1}, \ldots, i_1^n$ are uniformly distributed, the number $x + i_1^1 + i_1^2 + \cdots + i_1^{j-1} + i_1^{j+1} + \cdots + i_1^n$ $(\text{mod}\, s)$ is always uniformly distributed over M_j no matter what integer x is.
b. The distribution over $A_{-j} = \times_{j' \neq j} A_{j'}$, is uniform given that the input of player j is (i_1^j, i_2^j) and that the output is s', for every (i_1^j, i_2^j) and s'. To show this, note that for every player y the action prescribed by f'_y depends only on i_2^y and on s'. Moreover, since i_2^j is uniformly distributed, the action is also uniformly distributed. Exactly the same argument holds for the conditional probability over A_y given the actions of *all* other players and given s'; the conditional probability is always uniform.

As the conditional probability over every A_y given all other players' actions is uniform, we may conclude that the distribution over A induced by f', g'_{-j} and any g''_j is uniform.

We proceed now to the second stage of the construction, and similar to the example in Section 2, we inflate the input sets and the output set.

Suppose that all the probabilities of P are of the form c/d, where d is the common denominator. Let u be the lowest common multiplier of the numerators. In particular, all the numerators, c, divide the integer u. Denote the probability of the joint actions $a = (a_1, \ldots, a_n)$ by $P(a)/d$.

The idea is to basically keep the same input sets as before. However, instead of the output T', which is a number, we put a $u \times u$ matrix consisting of only two symbols: asterisk, *, and the number determined by T'. This matrix is determined by the probability assigned by P to the joint action corresponding (according to $f'_1, \ldots, f'_n$) the input–output combination. If the joint action is a, the number determined by T' is replicated $P(a)$ times. In the $u \times u$ matrix mentioned above in any row or column there are $P(a)$ cells in which the number determined by T' appear. All the rest are *.

Formally, the mediated talk, D, is defined as follows. The input sets of players $3, 4, \ldots, n$ will not be changed and remain I'_j $(I_j = I'_j$ for $j \geq 3)$. Players 1 and 2 will have different input sets: $I_j = I'_j \times \{1, \ldots, u\}$, $j = 1, 2$. Players 1 and 2 will choose a random element in I_j according to the uniform distribution.

The output T is either equal to T' or to $*$. This is determined by the input of players 1 and 2 as described here:

Denote by $Q(x, c)$ the $u \times u$ matrix

$$S' = \begin{bmatrix} X & & & & & & \\ & X & & & & * & \\ & & X & & & & \\ & * & & X & & & \\ & & & & \cdot & & \\ & & & & & \cdot & \\ & & & & & & \cdot \\ & & & & & & X \end{bmatrix}.$$

where X is a $c \times c$ matrix built of the entries x. Thus, $Q(x, c)$ is a matrix with entries that are either x or $*$. For instance, $Q(1, 2)$, where u is 4 is the matrix

$$\begin{pmatrix} 1 & 1 & * & * \\ 1 & 1 & * & * \\ * & * & 1 & 1 \\ * & * & 1 & 1 \end{pmatrix}.$$

If $c = 0$, then the matrix consists of asterisks only.

Suppose now that the input combination is

$$i = ((i_1^1, i_2^1, i_3^1), (i_1^2, i_2^2, i_3^2), (i_1^3, i_2^3), \ldots, (i_1^n, i_2^n)).$$

(The inputs of players 1 and 2 are triples and of the rest are pairs.) Let i' be i without the third coordinates of the inputs of players 1 and 2. $T'(i')$ is the output of the auxiliary mediated talk. The output $T'(i')$ and i' correspond to a certain joint action in A (through the strategies $f'_1, f'_2, \ldots, f'_n$). Denote it by $a(i')$. Now define $T(i)$ to be the (i_3^1, i_3^2) entry of the matrix $Q(T'(i'), P(a(i')))$.

Notice that in every row and every column of the matrix $Q(T'(i'), P(a(i')))$ there are exactly $P(a(i'))$ times $T'(i')$ and $u - P(a(i'))$ times $*$. $T'(i')$ is therefore replicated $P(a(i'))$ times.

The output $*$ is the only element in K_j. Thus, when a player gets $*$, he knows that the communication phase must continue. The conversation policy then will prescribe to repeat the process all over again: to choose an element according to the same distribution from I_j and so on. However, if $T(i)$ is not $*$ it means that the game should start and the actions to be chosen depend only on the last output. That is, we identify f_j with f'_j.

In short, in the second stage of the construction we multiplied the appearance of those outputs that correspond to the joint action a by $P(a)$. It is done in such a way that players 1 and 2 who jointly control whether the talk will continue or stop cannot unilaterally change the frequency of numbers (which eventually determine the actions) and asterisks.

According to the first phase, all the actions $a \in A$ appear uniformly given any output. Now, after the second phase, any joint action, a, is multiplied by $P(a)$. Since the sum of all the $P(a)$'s is d, the weight of a is precisely $P(a)/d$.

In changing the conversation policy, no player has a way to unilaterally affect the distribution over A. The induced distribution is P. Moreover, P induces a correlated strategy and, therefore, there is no incentive to deviate from f_j. We conclude that D and $(f_1, \ldots, f_n)$ generate P, as desired, and that the communication phase is finite with probability 1.

5 Concluding Remarks

a Generalization of Jointly Controlled Lottery

In Aumann and Maschler (1966), the idea of jointly controlled lottery was introduced. Two players have to jointly choose one of a few elements. For instance, suppose that one of two elements, 0 and 1, is to be selected by two players with probability 1/2 without anyone being able to affect the choice. The joint lottery is conducted as follows. Each player chooses independently with equal probabilities 2 and or 3 and the element selected is the sum of the two players' selections modulo 2.

This example can be described also by the following matrix

Input and player II

Input of player I		2	3
	2	0	1
	3	1	0

output

As in the example of Chapter 2, the distribution over inputs (2 or 3) is uniform. Since the distribution over the final choice (0 or 1) in every row is the same, there is no advantage for player I in altering to a non-uniform distribution. This property (and a similar one for player II) is what characterizes the jointly controlled lottery and we used it in generating uniform distribution over a matrix in the first phase of the construction. See also Sorin (1980) for a comprehensive exposition of the subject.

b Espionage-Free Mechanism

By espionage we mean that an outside observer knows not only the public outcome but also the output function, T. Thus, he knows the precise description of the mediating machine. Does this additional information provide him with some advantage? The answer is no, because given any output and T (the inputs are secret) the mechanism assigns the distribution P to A. The details found by a spy cannot reveal anything more than that. Once again, it assumes that the inputs are kept concealed and that only the mechanism itself becomes known.

c Finiteness of the Talk

The construction introduced above suggested a talk phase which is finite with probability 1. The problem of finding a bounded process (public mediated talk) that induces any rational correlation P is still open.

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