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**COMMUNICATION, COMPLEXITY, AND
EVOLUTIONARY STABILITY**

by Karl Wärneryd

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Communication, Complexity, and Evolutionary Stability

Karl Wärneryd*

February 19, 1993

Abstract

In games with costless preplay communication, some strategies are more complex than others in the sense that they induce a finer partition of the set of states of the world. This paper shows that if the concept of evolutionary stability, which is argued to be a natural solution concept for communication games, is modified to take lexicographic complexity preferences into account, then for a class of games of common interest only communication strategies that induce payoff-dominant Nash outcomes of the underlying game are stable.

1 Introduction

Much of economic theory deals with coordination problems. The perhaps most basic is the exploitation of potential gains from trade. In game-theoretic terms, this is the problem of coordinating on a payoff-dominant equilibrium out of a larger set of equilibria. (Such behavior is sometimes called *cooperation*.)

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If the players of a game are allowed to communicate before taking actions, we have a strong intuition that they will achieve coordination. The subfield of cooperative game theory is partly based on this intuition.

For a long time it seems to have been taken more or less for granted that explicit modeling of communication opportunities would support the intuition as a formal result in a straightforward manner. As it turns out, there are complications. The only immediate effect of adding a preplay communication stage where costless, e g, verbal, messages can be sent to a one-shot game is an expansion of the set of equilibrium outcomes to include correlated equilibrium payoffs (see, e g, Wärneryd [17]).

Some authors (notably Farrell [6, 7]) have recently dealt with this by assuming the messages have established meanings in some language held in common by the players. If the players adhere to such meanings when there are no positive incentives not to, a refinement of the set of equilibria may be the result. It is hard to see, however, how this amounts to much more than assuming what is to be proved, namely that communication allows the players to coordinate. The “semantic” approach begs the question of where those meanings come from in the first place.

A less philosophically problematic approach sees meaning as an equilibrium property of messages at stationary states of some evolutionary or trial-and-error process. This line of thinking was intuitively suggested in the early work of Crawford and Sobel [5], and is formally developed in, e g, Kim and Sobel [9], Matsui [10], and Wärneryd [16, 18].

The present paper falls in the latter category, but differs in applying the idea of lexicographic complexity preferences in the spirit of Binmore and Samuelson [4]. There is a natural complexity measure for “languages” in the sense of these models. A language is more complex the more finely it distinguishes between different possible messages, i e, the more nuances it has. The intuition behind the results in this paper is that if such complexity is costly, it can only be used to coordinate on efficient solutions. Anderlini [1] also discusses complexity issues in the context of communication in coordination games, but from the standpoint of perturbations of *a priori* restricted sets of strategies.

The paper is organized as follows. Section 2 presents the general model. The concept of evolutionary stability is defined in Section 3, which also discusses evolutionary approaches to communication games without complexity considerations. Section 4 in-

roduces a complexity measure for the model, and discusses its motivation. A payoff function that takes complexity into account in a lexicographic manner is constructed, and evolutionary stability redefined in terms of it. Section 5 contains a result on efficiency and stability (under the complexity-adjusted stability notion) in common interest games where only pure communication strategies can be used. Finally, Section 6 warns the reader that if mixed strategies are allowed, the result does not carry over. Furthermore, in the population game setting implied by the use of notions of evolutionary stability, there will always be asymmetric population distributions of inefficient strategies that can persist.

2 Preliminaries

Let G be a two-player, symmetric normal form game with a finite set A of pure strategies (actions) available to both players, and a payoff function $u : A \times A \rightarrow \mathfrak{R}$. If $x = (a, a') \in A \times A$ is an action profile of G , define $\hat{x} := (a', a)$. Thus if $u(y)$ is the payoff of one player when the profile y is played, $u(\hat{y})$ is the payoff of his opponent. Let $N(G)$ denote the set of pure strategy Nash equilibria of G .

We shall consider games extended by a preplay communication stage where the players simultaneously each send a costless message from the common finite message set M . The messages are observed by both players before they play G . The messages are not assumed to have any conventional meanings that enter into the deliberations of agents. The only thing that distinguishes a message set is its number of elements. It is assumed throughout that $|M| \geq 2$ (where $|X|$ denotes the number of elements, or cardinality, of a set X). Call the communication-extended game G^* .

A pure strategy of the reduced normal form of G^* consists of a message $m \in M$ and a function $\alpha : M \rightarrow A$ that prescribes an action of G for every possible message sent by the opponent. Let S be the set of pure strategies. Note that our construction implies that we rule out self-inconsistent behavior. A player need not plan an action at information sets other than those in which he has sent the signal specified by the strategy. One might think that the possibility of mistakes at the message stage should be allowed for. But we shall think of strategies as minimal finite-state machines for playing G^* . Such machines

	a_1	a_2
a_1	3, 3	0, 0
a_2	0, 0	1, 1

Figure 1: A game of common interest.

have no states for messages not sent by the strategy, and could therefore not send them even by mistake.

We consider only pure strategies. The payoff function of the communication-extended game is defined as $U(m\alpha, m'\alpha') := u(\alpha(m'), \alpha'(m))$. However, we also need to define payoffs to mixed strategies for use in defining evolutionary stability later. Let $\sigma : S \rightarrow [0, 1]$ such that $\sum_S \sigma(s) = 1$ be a mixed strategy. With no risk of confusion, we shall say that $U(\sigma, \sigma') := \sum_S \sum_{S'} \sigma(s) \sigma'(s') U(s, s')$.

The possibility of communication by itself does not guarantee cooperation if added to a one-shot game. As an example, consider the game in Figure 1. This game exhibits *common interest*, a property that will be formally defined later but has an obvious meaning here. Although it seems reasonable to think that players who could communicate would be able to coordinate on the payoff-dominant (a_1, a_1) equilibrium and rule out anything else, communication of the fairly general form we have introduced here does not yield this result. Consider a situation where both players play strategies $m\alpha$ where $\alpha(m') = a_2$ for all m' . This is a Nash equilibrium since a best reply to $m\alpha$ can do no better than play a_2 when the opponent sends m , yielding the same inefficient expected payoff.

This general problem is sometimes expressed by saying that every game of costless communication has inefficient “babbling” equilibria, where messages are ignored. It is this problem in particular that motivates the approach taken in this paper.

3 Evolutionary Stability

Of course one should not expect players to be able to come to a one-shot game and utilize abstract symbols, that have no prior established meanings, to coordinate. We must study games that are played repeatedly. Repeated games, as such, are not what we want, however. A repeated game is just one big game, and with communication it will

suffer from the same problems as any other isolated game. To understand the origin of conventions of language that allow players to coordinate, we must look at games that are played many times by different combinations of players and evolve over time, i.e., we must study evolutionary games.

A convenient way of doing this, that avoids complications associated with dealing with explicit dynamical systems, is to apply the concept of an evolutionarily stable strategy, defined for a general game by Maynard Smith [11] as follows.

Definition 1 *Let Γ be a symmetric normal form two-player game with (mixed) strategy set Σ and payoff function $\pi : \Sigma \times \Sigma \rightarrow \mathbb{R}$. A strategy $\sigma^* \in \Sigma$ is said to be an evolutionarily stable strategy (ESS) of Γ if for all $\sigma \neq \sigma^*$*

$$\pi(\sigma^*, \sigma^*) > \pi(\sigma, \sigma^*),$$

or

$$\pi(\sigma^*, \sigma^*) = \pi(\sigma, \sigma^*) \text{ and } \pi(\sigma^*, \sigma) > \pi(\sigma, \sigma).$$

Think of the game as being played by a large population of players who are repeatedly randomly matched in pairs. The criterion is then equivalent to requiring that, if all agents play the ESS, a small invasion of agents playing some other strategy should do strictly worse than the ESS players. That is, the above conditions are equivalent to saying there exists $\delta > 0$ such that for all $\sigma \neq \sigma^*$ and all $\epsilon \in (0, \delta)$,

$$\pi(\sigma^*, (1 - \epsilon)\sigma^* + \epsilon\sigma) > \pi(\sigma, (1 - \epsilon)\sigma^* + \epsilon\sigma).$$

In biological game theory, the ESS notion is usually justified by reference to the fact that an ESS is an asymptotically stable fixpoint of the so-called replicator dynamics, a model of asexual genetic reproduction. (See, e.g., Taylor and Jonker [14].) For economic applications, we would rather think of the strategy population as evolving through a process of learning or imitation. Clearly, however, the ESS concept is a reasonable notion of stability also in such a setting. If anything, it is too strong a requirement. In many games, an ESS fails to exist. We shall therefore also use a weakening of the ESS conditions called *neutral stability*, which only requires that a mutant does not do strictly better against the perturbed population than does the incumbent. That is, a strategy σ^* will be

said to be neutrally stable if there is $\delta > 0$ such that for all $\sigma \neq \sigma^*$ and all $\epsilon \in (0, \delta)$, we have that

$$\pi(\sigma^*, (1 - \epsilon)\sigma^* + \epsilon\sigma) \geq \pi(\sigma, (1 - \epsilon)\sigma^* + \epsilon\sigma).$$

The effect of this is to weaken the second inequality of the equivalent two-part definition.¹

We note that both a_1 and a_2 are ESSs of the game in Figure 1. So evolutionary stability in itself is not enough to rule out inefficient play. However, Robson [12] suggests that communication possibilities in combination with evolution will help. This is because if communication possibilities are not utilized, a mutant that communicates with players of its own type in order to coordinate on the efficient outcome could arise and eventually reproduce to supplant the original population. Robson shows that in every game that has an inefficient ESS it is possible to construct a mutant that recognizes its own type and destabilizes the inefficient ESS.

A problem with Robson's approach is that it fails to consider the entire set of possible mutants. Once you admit the idea of a signaling mutant, what is there to stop evolution from introducing mutants that use the signal in other ways? For the analysis to be complete, we must study the stability of efficiency-inducing mutants in a situation where any kind of mutant could arise, i.e., in the general setting described in the previous section.

Such an inquiry gives a limited positive result.

Proposition 1 *Let G be a 2×2 game of the form*

	a_1	a_2
a_1	u_H, u_H	$0, 0$
a_2	$0, 0$	u_L, u_L

where $u_H > u_L > 0$. Then s is a neutrally stable pure strategy of the communication-extended game G^* if and only if $U(s, s) = u_H$.

A proof is given in Wärneryd [18].

This result does not extend beyond the class of 2×2 games, however. To see why, consider the counterexample of the game in Figure 2.

¹There is a dynamic justification also for neutrally stable strategies. Weibull [19] shows that they are Lyapunov-stable fixpoints of the replicator dynamic. Similar results are discussed in Thomas [15].

	a_1	a_2	a_3
a_1	3, 3	0, 0	0, 0
a_2	0, 0	2, 2	0, 0
a_3	0, 0	0, 0	1, 1

Figure 2: A counterexample.

Consider the strategy $m_1\alpha$ of the communication-extended game such that

$$\alpha(m) = \begin{cases} a_2 & \text{if } m = m_1 \\ a_3 & \text{otherwise.} \end{cases}$$

This is a neutrally stable strategy since any alternative best reply to $m_1\alpha$ must also send m_1 (otherwise it could get at most a payoff of 1) and respond with a_2 to m_1 . But then it also gets a payoff of 2 when it meets itself. So $m_1\alpha$ sustains an inefficient payoff by threatening to do something even worse.

However, it could be argued that $m_1\alpha$ is an unnecessarily complicated way of getting a payoff of 2. You could get that by not bothering to distinguish between messages at all and just responding with a_2 to everything.

Consider a population where everybody plays $m_1\alpha$. A mutant could arise that also sends m_1 but then always plays a_2 regardless of the message sent by the opponent. Since the mutant gives rise to the same payoff, it seems reasonable to think that the population distribution could drift over to favor the mutant. But then a population dominated by the mutant could be invaded by a strategy that sends a different message and plays a_1 against itself.

A form of this argument is the basis for the set-valued stability notion approaches of Kim and Sobel [9] and Matsui [10]. In the following, we shall explore a slightly different approach that takes complexity considerations into account explicitly. The drifting away of inefficiency-inducing strategies will be assumed to happen because evolution directly favors less complex strategies.

4 Complexity

In general, any strategy or decision rule can be viewed as a function from some set Ω of states of the world to a set of actions. Such a function induces a partition of Ω into equivalence classes of states of the world that induce the play of the same action. The degree of complexity of a strategy will here be identified with the fineness of its implicit partition of the set of states of the world. This reflects the idea that a strategy is more complicated and costly the more different ways it has of conditioning on past events, or, put differently, the more detailed is the information it requires.

The application of complexity measures is perhaps best known from the theory of repeated games, and the most common measure is that of the number of states required by the unique minimal deterministic finite-state machine (henceforth, DFM)² that implements the strategy (see, e g, Rubinstein [13]). This measure is shown by Kalai and Stanford [8] to be equivalent to the definition given above given a suitable definition of the state space. In particular, the definition utilizes the recursive nature of repeated game histories.

For the present application, the minimal DFM that implements a given strategy of the communication game has a trivial structure. In fact, given the way strategies have been specified above, a strategy may be directly identified with its minimal machine implementation. Consider the strategy $s = m\alpha$. The minimal machine has an initial output state outputting the message m , and then transits to final output states as a function of an opponent's message input according to α , which may thus be regarded as a transition function. The final output states correspond to the actions in the range of α . A minimal machine implementation of s therefore has $1 + |\alpha(M)|$ states. Disregarding the initial output state that every machine has to have, we shall call $c(m\alpha) := |\alpha(M)|$ the *complexity* of $m\alpha$. Clearly, the least complexity a strategy could have is 1, which corresponds to playing the same action regardless of the opponent's message, and the greatest is $\min\{|A|, |M|\}$, which corresponds to discriminating perfectly between different messages sent by the opponent.

²In the following I assume some very limited familiarity with the theory of finite-state machines. Such knowledge is not necessary to understand any of the results of this paper, however.

We now modify the payoffs to take into account the complexity of a strategy in a lexicographic manner. Let U^c be the complexity-adjusted payoff function. We shall say that

1. $U^c(s, s') > U^c(s'', s')$ if $U(s, s') > U(s'', s')$ or if $U(s, s') = U(s'', s')$ and $c(s) < c(s'')$.

It follows that

2. $U^c(s, s') \geq U^c(s'', s')$ if $U(s, s') > U(s'', s')$ or if $U(s, s') = U(s'', s')$ and $c(s) \leq c(s'')$.

We now wish to incorporate these complexity-adjusted preferences into a notion of evolutionary stability. A major problem with the strength of the ESS criterion is that, in general, an ESS does not always exist. In particular, the games considered here typically fail to have an ESS in pure strategies. This is because as a consequence of the lexicographic complexity preferences a necessary requirement for stability will turn out to be that a strategy has complexity 1, i.e., that it always plays the same action. But then any other strategy that also always plays the same action, but sends a different initial message, will be an alternative best reply that does as well against itself as the first strategy does against it.

Since it seems reasonable not to care about the distinction between strategies that in effect behave alike when faced with one another and can thus stably coexist, we shall consider strategies that are neutrally stable in terms of the lexicographic complexity-adjusted payoff function instead. We therefore require of a strategy s for it to be considered stable that for every $s' \neq s$ there exist $\delta > 0$ such that for all $\epsilon \in (0, \delta)$,

$$U^c(s, (1 - \epsilon)s + \epsilon s') \geq U^c(s', (1 - \epsilon)s + \epsilon s').$$

This is the case if either

$$(1 - \epsilon)U(s, s) + \epsilon U(s, s') > (1 - \epsilon)U(s', s) + \epsilon U(s', s') \text{ for all } \epsilon \in (0, \delta)$$

or

$$(1 - \epsilon)U(s, s) + \epsilon U(s, s') = (1 - \epsilon)U(s', s) + \epsilon U(s', s') \text{ and } c(s) \leq c(s') \text{ for all } \epsilon \in (0, \delta).$$

The following equivalent definition is easier to apply in practice.³

³This is the same thing, except of course for the difference in the intended application, as what Binmore and Samuelson [4] call a *modified evolutionary stable strategy*. Also, the exact motivation for the concept is slightly unclear from their paper.

Definition 2 A strategy s of G^* is said to be neutrally stable with respect to U^c (c -stable) if for all $s' \neq s$

$$U(s, s) > U(s', s)$$

or

$$U(s, s) = U(s', s) \text{ and } U(s, s') > U(s', s')$$

or

$$U(s, s) = U(s', s) \text{ and } U(s, s') = U(s', s') \text{ and } c(s) \leq c(s').$$

Observe that with a lexicographic utility function there is no longer an equivalence between the two-part definition of a neutrally stable strategy and the definition in terms of stability in the face of a small invasion of mutants. Furthermore, a c -stable strategy is not necessarily in Nash equilibrium with itself in terms of the lexicographic utility function.

We note that if a strategy is an ESS in ordinary payoff terms alone, it satisfies the first two conditions and is c -stable.

The following result is immediate.

Proposition 2 If s is a c -stable strategy of G^* , then $c(s) = 1$.

PROOF. Let $s = m\alpha$ be some strategy with $c(s) > 1$. Consider the alternative best reply $s' = m\alpha'$ such that $\alpha'(m') = \alpha(m)$ for all m' . We have that $U(s', s') = U(s, s') = U(s', s) = U(s, s)$, but $c(s') = 1 < c(s)$, so s is not c -stable. $\square$

Note that this means that c -stable strategies are necessarily of the “babbling” kind, where in effect no communication takes place. Yet, as we shall see below, the *potential* for effective communication in the model forces efficient behavior in some types of games. There is a similarity to the results of Ben-Porath and Dekel [3], who do not study costless communication, but allow players to “burn money,” i.e., unilaterally decrease their expected utility, before a game is played. In pure coordination games, the strategies that survive iterated elimination of weakly dominated strategies induce efficient outcomes without any money actually being burnt.

5 Common Interest

Aumann and Sorin [2] discuss a class of games that have a unique payoff profile that strictly dominates all other feasible payoff profiles. The following definition utilizes the fact that in a symmetric game, such a payoff profile if it exists must give both players the same payoff.

Definition 3 *G is said to be a game of common interest if there is $\bar{u}$ such that $u(x) = u(\hat{x}) = \bar{u}$ for some $x \in A \times A$, and for all $y \in A \times A$, if $(u(y), u(\hat{y})) \neq (\bar{u}, \bar{u})$, then $u(y) < \bar{u}$ and $u(\hat{y}) < \bar{u}$.*

It should be stressed that an obvious necessary condition for the existence of a c -stable strategy is that G has a symmetric pure strategy equilibrium. Accordingly, the following result does not guarantee existence of a c -stable strategy.

Proposition 3 *If G is a game of common interest and there is $x \in A \times A$ such that $u(x) = \bar{u}$ and $x = \hat{x}$, then a strategy s of G^* is c -stable if and only if $U(s, s) = \bar{u}$ and $c(s) = 1$.*

PROOF. To prove the “if” part, let $s = m\alpha$ be such that $U(s, s) = \bar{u}$ and $c(s) = 1$. Clearly, no strategy can do strictly better against s . Let s' be an alternative best reply to s . We have that $U(s', s) = \bar{u}$. Since G is a game of common interest, where if one player gets $\bar{u}$ so does his opponent, we have that $U(s, s') = U(s', s) = \bar{u}$. Then since $\bar{u} \geq U(s', s')$ and $c(s') \geq 1$, s is c -stable.

To prove the “only if” part, we start by noting that by Proposition 2 s cannot be c -stable if $c(s) > 1$. So we need only consider strategies of complexity 1. Let s be such that $c(s) = 1$, but $U(s, s) < \bar{u}$. We can find an alternative best reply $s' = m'\alpha'$ such that $m' \neq m$, $\alpha'(m) = \alpha(m') = \alpha(m)$, and $u(\alpha'(m'), \alpha'(m')) = \bar{u}$. Since $U(s', s') = \bar{u} > U(s, s') = U(s, s)$, s is not c -stable. $\square$

6 Caveat

If mixed strategies are allowed, the efficiency result from the previous section does not hold anymore. As an example of this, consider again the game in Figure 1. Let the

communication-extended game have a message set consisting of two messages, m_1 and m_2 . Consider the two pure strategies $s_1 = m_1\alpha_1$ and $s_2 = m_2\alpha_2$ such that

$$\alpha_1(m) = \begin{cases} a_2 & \text{if } m = m_1 \\ a_1 & \text{if } m = m_2, \end{cases}$$

and

$$\alpha_2(m) = \begin{cases} a_1 & \text{if } m = m_1 \\ a_2 & \text{if } m = m_2. \end{cases}$$

Now construct a mixed strategy σ that plays s_1 and s_2 with equal probability. We have that $U(\sigma, \sigma) = 2$.

Regardless of how we choose to define a complexity measure for mixed strategies, σ cannot be destabilized, because it is an ESS already strictly in payoff terms. This means complexity considerations will not even enter the picture.

To see that σ is an ESS, consider alternative best replies to σ . Clearly, any alternative best reply must after having sent m_1 behave like s_1 , and after having sent m_2 like s_2 . So let σ' be a probability mix of s_1 and s_2 different from that of σ . We have that $U(\sigma', \sigma') < U(\sigma, \sigma) = 2$, so σ is an ESS.

This problem extends also to the pure-strategy case if the random-matching story underlying the use of the stability concept is taken seriously. Then even if only pure strategies can be played, there are stable asymmetric population distributions of strategies that induce inefficient outcomes. As an example, consider a population faced with the game discussed above where half of the agents play s_1 and half play s_2 . In complete analogy with the mixed strategy case, no strategy can invade such a population.

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