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Evolution of Interdependent Preferences in Aggregative Games*

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Abstract

We study the evolution of preference interdependence in aggregative games which are symmetric with respect to material payoffs but asymmetric with respect to player objective functions. Specifically, some players have interdependent preferences (in the sense that they care not only about their own material payoffs but also about their payoffs relative to others) while the remainder are (material) payoff maximizers in the standard sense. We identify a class of aggregative games whose equilibria have the property that the players with interdependent preferences earn strictly higher material payoffs than do the material payoff maximizers. Included in the class are common pool resource and public good games. If each member of the population interacts with each other member (the playing-the-field model), we show that any evolutionary selection dynamic satisfying a weak payoff monotonicity condition implies that only interdependent preferences can survive in the long run.

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1 Introduction

A standard assumption in the economic modeling of human behavior is that people have independent preferences. Given a choice between two income distributions, they will prefer that in which their own income is higher, regardless of their rank or relative standing in the two distributions. Changes in the incomes of others, provided that their own material circumstances remain unchanged, leave them neither better nor worse off, and they are consequently unwilling to sacrifice any portion of their own material well-being in order to enhance or to diminish the well being of others.

The usual methodological defense of independent preferences is made on evolutionary grounds: units which maximize their own material payoffs will prosper and thrive, while those that do not will be outperformed and driven to eventual extinction (Friedman, 1953). While compelling in the context of perfectly competitive environments, this evolutionary argument runs into difficulties in imperfectly competitive settings. It is possible in some strategic environments that individuals who care only about their own material well-being obtain strictly lower material rewards in equilibrium than similarly situated individuals who are also concerned with the well-being of others. Our purpose in the present paper is to identify strategic environments of economic importance which give rise to this phenomenon. Specifically, we identify games in which players with independent preferences, who care only about their own (material) payoffs, earn strictly lower material payoffs in equilibrium than do players with *interdependent* preferences, who care additionally about their payoffs relative to others.

This disparity in equilibrium payoffs has implications for the theory of preference formation. Recent work dealing with the evolution of preferences in strategic environments is based on the methodology that individuals within a generation behave rationally with respect to their inherited (or acquired) preferences, but that the distribution of preferences across the population changes from one generation to the next under pressure of differential material rewards.[1] It is typically assumed in this literature that the evolutionary selection dynamics are *payoff monotonic,* i.e., higher material payoffs to a heritable trait typically lead to more rapid replication of that trait over time. Consequently, the finding that the

[1] Applications of this methodology include evolutionary explanations of time preference (Rogers, 1994), risk-aversion (Robson, 1996), reciprocity (Güth and Yaari, 1992), altruism among siblings (Bergstrom, 1995), altruism in general (Bester and Güth, 1998), preferences for social status (Fershtman and Weiss, 1996), and systematic errors in expectations (Waldman, 1994). For an alternative and complementary approach to preference formation based on forward-looking parental socialization see Bisin and Verdier (1997).

material rewards to those with interdependent preferences strictly exceed the rewards to those with independent preferences leads directly to the implication that evolution will favor the persistence of interdependent preferences in particular classes of strategic environments.

The strategic environments that we consider are *aggregative games*, in which the (material) payoff to any given player depends only on her own action and some aggregate of the actions of all players. The general problem of preference formation can, of course, be studied within the context of any strategic environment. Our focus on aggregative games is motivated by the fact that such environments include common pool resource extraction and public good games, which have been a perennial feature of human societies from the earliest times. Traditional societies even in the present day rely heavily on commonly owned fisheries, grazing lands, and forest areas for their subsistence. Similarly, throughout human history, a large number of essential activities have required collective action of one kind or another, ranging from the hunting of large animals and the construction of housing to the provision of irrigation, harvesting, and defense against encroachment or attack by competing groups. If such environments favor the emergence of preference interdependence, then the use of interdependent preferences to explain experimental and empirical anomalies, and in economic modeling more generally, may be justified on evolutionary grounds.[2]

The paper is organized as follows. In Section 2, we introduce a formal framework which makes precise the idea that one type of preference may have a *strategic advantage* over another. In Section 3 we identify a class of aggregative games in which players with interdependent preferences have a strategic advantage over those with independent preferences, and show that standard models of common pool resource extraction and public good provision belong to this class. The evolutionary implications of our findings are explored in Section 4, in which it is argued that when each member of the population interacts simultaneously with every other member (the "playing the field" model), independent preferences cannot survive in the long-run.[3] Section 5 concludes with a discussion of possible extensions and additional applications of our results.

[2] The importance and plausibility of interdependent preferences has often been noted (Duesenberry, 1949, Frank, 1987, and Cole, Mailath and Postlewaite, 1992), and is supported by ample empirical and experimental evidence (see Clark and Oswald, 1996, and references cited therein). It is also well known that the introduction of interdependent preferences into economic models has non-trivial implications in that many conventional results have been either overturned or significantly modified in the presence of such preferences.

[3] This result need not hold when individuals are matched to play games within smaller subgroups (as is the case in pairwise random matching models). For reasons discussed in Section 4, however, the playing-the-field hypothesis is particularly appropriate in the analysis of aggregative games.

2 The Nature of the Problem

Let $a < b < \infty$ and consider any symmetric n-person normal form game

$$\Gamma \equiv \left(\{[a,b], \pi_r\}_{r=1,\ldots,n} \right),$$

where $[a,b]$ and $\pi_r : [a,b]^n \to \mathbb{R}_{++}$ stand for the action space and the *material* payoff function of player r, respectively. The set of all such games is denoted by $\mathcal{G}$. We let $\bar{\pi}(x) \equiv \sum \pi_r(x)/n$ denote the mean material payoff at the action profile x, and define

$$\rho_r(x) \equiv \frac{\pi_r(x)}{\bar{\pi}(x)}, \quad x \in [a,b]^n.$$

Here $\rho_r(x)$ stands for the *relative* payoff of individual r at action profile x.[4]

It is important to distinguish between material payoffs and objective functions because we permit individuals to have objective functions that do not simply require the maximization of material payoffs. Specifically, we suppose that only $k \in \{1, 2, ..., n-1\}$ players are material payoff maximizers in the usual sense; their objective functions are increasing in their own material payoffs and do not depend on the material payoffs of others. Such persons will be said to have *independent preferences.* The remaining players are concerned not only with their own material payoffs but also with their relative payoffs as defined above. To introduce the preferences of these individuals formally, let us first define the following collection of real functions:

$$\mathcal{F} \equiv \{F : \mathbb{R}^2_{++} \to \mathbb{R} : F \text{ is differentiable and } \partial_1 F, \partial_2 F > 0\}.^5$$

We say that a player j has (*negatively*) *interdependent preferences* if there exists an $F^j \in \mathcal{F}$ such that j's preferences are represented by an objective function $\Psi_{F^j} : [a,b]^n \to \mathbb{R}$ of the following form:

$$\Psi_{F^j}(x) \equiv F^j\left(\pi_j(x), \rho_j(x)\right) \tag{1}$$

This particular representation of (negatively) interdependent preferences has recently been proposed and axiomatically characterized by Ok and Koçkesen (1997). In particular, the preferences represented by (1) can be interpreted as a compromise between the standard case where the individual is assumed to care only about her absolute payoff π_j, and the

[4] To guarantee that ρ_r is well-defined, we assume throughout that the material payoff functions always take strictly positive values. Note that speaking of "relative payoffs" forces us to evaluate material payoff functions in a strictly *cardinal* manner. This is conceptually unproblematic when payoffs represent amounts of money, profits, or any homogeneous commodity.

[5] Here $\partial_i F$ represents the partial derivative of F with respect to its ith component.

extreme case where she is concerned exclusively with her relative payoff ρ_j. (The latter case corresponds to Duesenberry's relative income hypothesis.) The class of interdependent preferences we consider here is quite rich, and includes several specifications used elsewhere.[6]

Let $I_k \equiv \{1, ..., k\}$ represent the set of players with independent preferences, and $J_k \equiv \{k+1, ..., n\}$ the set of those with interdependent preferences. We shall assume that all objective functions are common knowledge. Hence the *actual* strategic interactions of the individuals are modeled by means of the normal form game where the rth player's action space is $[a, b]$ and her objective function is either π_r (if $r \in I_k$) or is given by (1) for some $F^r \in \mathcal{F}$ (if $r \in J_k$). Let us denote a generic game of this sort by $\Gamma_{\mathbf{F}}$, where $\mathbf{F} = (F^{k+1}, F^{k+2}, ...F^n) \in \mathcal{F}^{n-k}$ is the vector of interdependent objective functions. Formally, $\Gamma_{\mathbf{F}}$ is the normal form game $(\{[a, b], p_r\}_{r=1,...,n})$, where $p_r : [a, b]^n \to \mathbb{R}$ is defined as:

$$p_r \equiv \begin{cases} \pi_r, & r \in I_k \\ \Psi_{F^r}, & r \in J_k \end{cases} \tag{2}$$

with $F^r \in \mathcal{F}$, $r \in J_k$. Therefore, the primitives of our analysis are the symmetric n-player game Γ, the number of independent players k, and the vector of interdependent objective functions $\mathbf{F}$. Given these primitives, the game $\Gamma_{\mathbf{F}}$ is fully specified.

An immediate question of interest is the following: are there economically important classes of games Γ for which, regardless of the population composition k, and the vector of interdependent objective functions $\mathbf{F} \in \mathcal{F}^{n-k}$, it is the case that at any equilibrium action profile of the $\Gamma_{\mathbf{F}}$, the material payoff to *each* player with interdependent preferences exceeds the material payoff to *any* player with independent preferences? To state this question precisely, we introduce the following:

Definition. *Let $\Gamma \in \mathcal{G}$ and let $\mathbf{F} \in \mathcal{F}^{n-k}$ for some $k \in \{1, ..., n-1\}$. We say that interdependent preferences yield a* **strategic advantage** *over independent preferences in $\Gamma_{\mathbf{F}}$ if, at each Nash equilibrium x of $\Gamma_{\mathbf{F}}$,*

$$\pi_j(x) \geq \pi_i(x) \quad \textit{for all } (i, j) \in I_k \times J_k \tag{3}$$

and

$$\pi_j(x) > \pi_i(x) \quad \textit{for some } (i, j) \in I_k \times J_k. \tag{4}$$

[6] One interesting special case of our specification is that in which interdependent players maximize the difference between their payoff and the mean payoff, i.e., $p_j = \pi_j - \bar{\pi} = \pi_j(1 - \rho_j^{-1})$. Such objective functions are sometimes referred to as the "beat-the-average" functions (Shubik, 1980).

In the next section, we demonstrate that interdependent preferences yield a strategic advantage over independent preferences in a rich class of aggregative games, and provide two economically important examples of games which belong to this class. The evolutionary implications of this finding are then explored in Section 4.

3 Strategic Advantage

3.1 Aggregative Games

The symmetric game $\Gamma \equiv (\{[a,b], \pi_r\}_{r=1,\dots,n})$ is said to be *aggregative* if

$$\pi_r(x) = H\left(x_r, \sum_{q=1}^{n} x_q\right), \quad x \in [a,b]^n,\ r = 1, ..., n, \tag{5}$$

where $H : [a,b] \times [na, nb] \to \mathbb{R}_{++}$ is an arbitrary twice differentiable function.[7] (The terminology we use follows Dubey, Mas-Colell and Shubik, 1982; for a recent and extensive analysis of aggregative games, see Corchón, 1996.) Among many interesting aggregative games are the Cournot oligopoly, the common pool resource and public good games, and a number of search theoretic models.

Let Γ be an aggregative game, so that the payoff functions satisfy (5). Consider the following assumptions:

$$H_1 \gtrless 0, \quad H_2 \lesseqgtr 0, \quad H_{11} \leq 0, \quad H_{12} \leq 0 \tag{6}$$

and

$$|H_1(a, na)| \gtrless |H_2(a, na)| \text{ and } |H_1(b, nb)| \lesseqgtr |H_2(b, nb)|\,. \tag{7}$$

While the assumption (7) is made only to rule out some trivial boundary equilibria (and is standard in economic models), assumption (6) is quite crucial for the main result of this section.[8] We denote the class of all aggregative games that satisfy (6) and (7) by $\mathcal{A}$.

The following is the main result of this section.

[7] The entire analysis of this paper goes through in terms of *generalized* aggregative games in which $\pi_r(x) = H(x_r, \sum h(x_q))$ for all $x \in [a,b]^n$ and $r = 1, ..., n$, where $h : [a,b] \to \mathbb{R}$ is a continuous, strictly increasing and concave function, and $H : [a,b] \times [nh(a), nh(b)] \to \mathbb{R}_{++}$ is any C^2 function. The required modifications of the proofs are straightforward.

[8] Both (6) and (7) are readily satisfied, for instance, in any Cournot oligopoly model with linear cost and demand schedules, provided that the price level that corresponds to the industry capacity is above the unit cost. More general Cournot models and other interesting games also satisfy these assumptions; two such examples are given below.

Theorem 1. *Take any* $k \in \{1, ..., n-1\}$ *and any* $\mathbf{F} \in \mathcal{F}^{n-k}$. *For any aggregative game* $\Gamma \in \mathcal{A}$, *interdependent preferences have a strategic advantage over independent preferences in* $\Gamma_{\mathbf{F}}$.[9]

Proof. Let $\Gamma \in \mathcal{A}$ such that (5) holds with $H_1 > 0$ and $H_2 < 0$. (The proof of the case where $H_1 < 0$ and $H_2 > 0$ is analogous to that which follows.) Fix any $k \in \{1, ..., n-1\}$ and $\mathbf{F} \in \mathcal{F}^{n-k}$, and let x be a Nash equilibrium of $\Gamma_{\mathbf{F}}$. We begin with a preliminary observation.

Claim 1. $x \neq (a, ..., a)$ and $x \neq (b, ..., b)$.

Proof of Claim 1. From the boundary condition $H_1(a, na) > |H_2(a, na)|$, it follows that there exists a small enough $\varepsilon > 0$ such that

$$\pi_i((a, ..., a) + \varepsilon e^i) = H(a + \varepsilon, na + \varepsilon) > H(a, na) = \pi_i(a, ..., a),$$

for all $i \in I_k$, where e^i is the ith unit vector. Since $I_k \neq \emptyset$, we conclude that $(a, ..., a)$ cannot be a Nash equilibrium. The second part of the claim is proved similarly. $\|$

Now define

$$A^1 \equiv \{i \in I_k : a < x_i \leq b\} \quad \text{and} \quad A^2 \equiv \{i \in I_k : x_i = a\}$$

and

$$B^1 \equiv \{j \in J_k : a \leq x_j < b\} \quad \text{and} \quad B^2 \equiv \{j \in J_k : x_j = b\}.$$

First consider the case in which $A^1 = \emptyset$. In this case, $H_1 > 0$ and (5) together imply (3) so, since $H_1 > 0$, the proposition fails to hold only if $x_j = a$ for all $j \in J_k$. But this would imply that $x_r = a$ for all $r = 1, ..., n$, contradicting Claim 1. Therefore, the proposition holds in the case $A^1 = \emptyset$.

Next consider the case $A^1 \neq \emptyset$. Let i^* be the smallest index that satisfies

$$i^* \in \arg\max_{i \in A^1} \; \pi_i(x),$$

and take any $j \in B^1$. Then, by definitions of Nash equilibrium and $\Gamma_{\mathbf{F}}$, we must have

$$\frac{\partial \pi_{i^*}(x)}{\partial x_{i^*}} \geq 0 \quad \text{and} \quad \frac{\partial p_j(x)}{\partial x_j} \leq 0. \tag{8}$$

[9] Theorem 1 continues to hold if the set I_k consists of players whose preferences are either independent or *positively* interdependent (the latter having objective functions $F_i(\pi_i, \rho_i)$ which are increasing in the first but decreasing in the second argument); the modification of the proof is straightforward.

By using (1) and (2), we can write the second inequality as

$$\begin{aligned}
\frac{\partial p_j(x)}{\partial x_j} &= \frac{\partial \pi_j}{\partial x_j}\left(\partial_1 F^j + \frac{1}{\bar{\pi}}\left(1 - \frac{\pi_j}{\sum \pi_q}\right)\partial_2 F^j\right) - \frac{1}{\bar{\pi}}\left(\frac{\pi_j}{\sum \pi_q}\right)\left(\sum_{r\neq j}\frac{\partial \pi_r}{\partial x_j}\right)\partial_2 F^j \\
&= \frac{\partial \pi_j}{\partial x_j}\left(\partial_1 F^j + \frac{1}{\bar{\pi}}\left(1 - \frac{\pi_j}{\sum \pi_q}\right)\partial_2 F^j\right) - \frac{1}{\bar{\pi}}\left(\frac{\pi_j}{\sum \pi_q}\right)\left(\sum_{r\neq j} H_2\left(x_r, \sum \pi_q\right)\right)\partial_2 F^j \\
&\leq 0,
\end{aligned}$$

where all the derivatives are evaluated at the equilibrium x. Since $H_2 < 0$, we must then have

$$\frac{\partial \pi_j}{\partial x_j}\left(\partial_1 F^j + \frac{1}{\bar{\pi}}\left(1 - \frac{\pi_j}{\sum \pi_r}\right)\partial_2 F^j\right) < 0$$

which is possible only if

$$\frac{\partial \pi_j(x)}{\partial x_j} < 0$$

since $\partial_1 F^j, \partial_2 F^j > 0$. By using this finding along with (5) and the first inequality of (8), we obtain

$$\left[H_1\left(x_j, \sum x_q\right) - H_1\left(x_{i^*}, \sum x_q\right)\right] + \left[H_2\left(x_j, \sum x_q\right) - H_2\left(x_{i^*}, \sum x_q\right)\right] < 0. \tag{9}$$

Now suppose that $x_{i^*} \geq x_j$. Since $H_{12} \leq 0$, we have $H_2\left(x_j, \sum x_q\right) \geq H_2\left(x_{i^*}, \sum x_q\right)$. Therefore, (9) yields

$$H_1\left(x_j, \sum x_q\right) < H_1\left(x_{i^*}, \sum x_q\right)$$

which contradicts that $H_{11} \leq 0$. Hence, we must have $x_{i^*} < x_j$. But then $H_1 > 0$ entails

$$\pi_j(x) = H\left(x_j, \sum x_q\right) > H\left(x_{i^*}, \sum x_q\right) = \pi_{i^*}(x),$$

whereas

$$\pi_{i^*}(x) \geq \pi_i(x) \quad \forall i \in I_k$$

by the choice of i^*. We have thus established the following claim.

Claim 2. $\pi_j(x) > \pi_i(x)$ for all $(i, j) \in I_k \times B^1$.

Notice that $H_1 > 0$ implies

$$\pi_j(x) \geq \pi_i(x) \quad \forall (i, j) \in I_k \times B^2.$$

Therefore, in view of Claim 2, the proof would be complete if $B^1 \neq \emptyset$ or if $x_i < b$ for some $i \in I_k$. But if neither of these statements holds, it must be the case that $x_r = b$ for all $r = 1, ..., n$, which contradicts Claim 1. ■

Theorem 1 identifies a class of aggregative games in which interdependent preferences yield a strategic advantage over independent preferences in terms of material payoffs. The following examples of well-known economic models show that the theorem is both easy to apply and that it has economic significance. The first of these examples also helps provide some intuition for the result.

3.2 Examples

3.2.1 Common Pool Resource Extraction

Consider a population consisting of n individuals, each of whom has access to a common pool resource. Let $x_r \geq 0$ denote the extraction effort chosen by individual r, while $X = \sum x_r$ denotes the aggregate extraction effort. There is an opportunity cost $w > 0$ per unit of extractive effort and each member of the population receives a share of the total product that is proportional to her share of aggregate extractive effort. Total product is given by a twice differentiable and bounded function $f : \mathbb{R}_+ \to \mathbb{R}_+$ with $f(0) = 0$ and $f'(0) > w$.

We let $A(X) \equiv f(X)/X$ stand for the average return to effort for all $X > 0$, and set $A(0) \equiv f'_+(0)$. It is standard to assume that $A'(X) < 0$ for all $X > 0$. Consequently, by the boundedness of f and $A(0) = f'(0) > w$, there must exist a unique $X_0 > 0$ such that $A(X) \lesseqgtr w$ whenever $X \gtreqless X_0$. We may then define the *common pool resource game* $\Gamma^{\text{cpr}} \equiv (\{[a, b], \pi_r\}_{r=1,\dots,n})$ by letting

$$\pi_r(x) = x_r \left(A(X) - w\right), \quad x \in [a, b]^n, \tag{10}$$

where $0 < a < b < X_0/n$.[10]

Γ^{cpr} is a minor modification of the widely-studied common pool resource game. Our modifications are two-fold. First, by requiring that extraction effort cannot fall below some (arbitrarily small) positive number a, we ensure that π_r is positive-valued and that the condition $H_2 < 0$ of Theorem 1 is satisfied Second, we assume that each individual's extractive effort is bounded in such a way that overcrowding can never be so extreme as to yield neg-

[10] This formulation, which closely follows Sethi and Somanathan (1996), is general enough to encompass a variety of institutional settings. For instance, if the output is for agents' own use and a labor market does not exist (as in pre-market societies) one would interpret w as the opportunity cost of the extraction effort in terms of other useful activities. If, on the other hand, the good is sold in a competitive market and a labor market exists, w can be interpreted as the foregone outside wage relative to the price of the product. If the output market is imperfectly competitive, $A(X)$ can be thought of as the product of a decreasing inverse demand function with the average product.

ative payoffs (i.e., $A(X) < w$). This too is required to ensure that π_r is positive-valued.[11] Given these assumptions, provided that a is sufficiently small and b is sufficiently large (i.e. provided that the action space is sufficiently rich), it is a straightforward matter to verify that $\Gamma^{cpr} \in \mathcal{A}$. Hence Theorem 1 immediately applies: interdependent preferences have a strategic advantage over independent preferences in the common pool resource game.

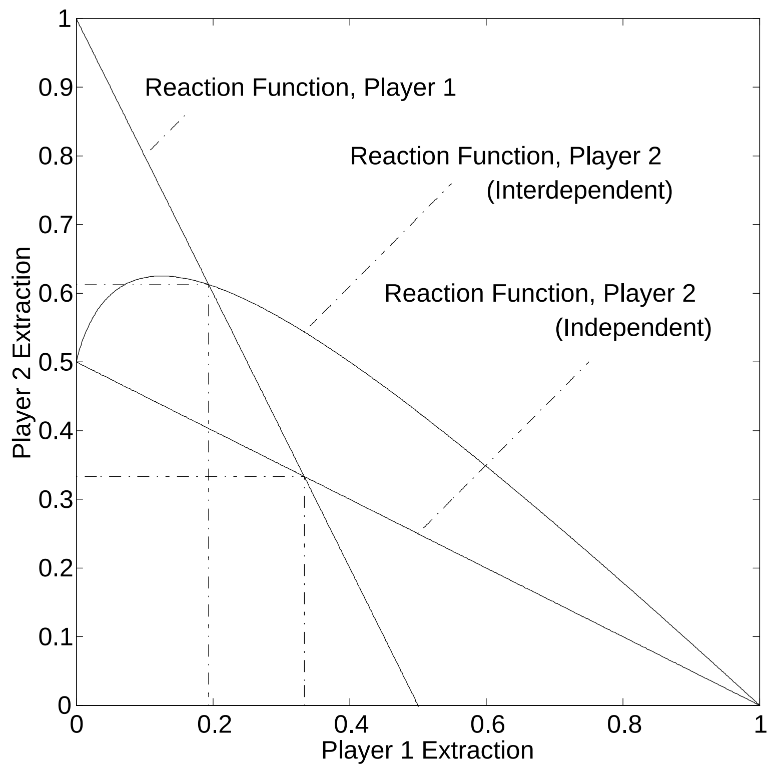

Figure 1: A Two-Player Common Pool Resource Game

The common pool resource game can also be used to provide some intuition for Theorem 1. The reaction curves for independent and interdependent players in a simple two-player version of this game are plotted in Figure 1 above.[12] In this game, if both players had independent preferences, the unique equilibrium would be symmetric with both players choosing extraction effort 0.33. However, player 2's reaction curve with interdependent preferences is everywhere above the one that she would have had with independent preferences.[13] Con-

[11] Both these assumptions can be relaxed without changing any of our conclusions, though some additional work is required in this case; see Kockesen et al. (1997a).

[12] The figure is based on the following specifications: $w = 1$, $F^2(\pi, \rho) = \pi^{.1}\rho^{.9}$, $f(X) = 2X - X^2$ for $X \in [0, 1]$ and $f(X) = 1$ for $X \geq 1$.

[13] It is important not to view Figure 1 as being generic. Theorem 1 holds regardless of whether the original reaction curves are downward sloping, and it need not be true that the reaction curve derived from p_i is in general "everywhere" above the one that is derived from π_i.

sequently, she is willing to extract more of the common pool resource at *every* choice of extraction level by the independent player (player 1), even if that means a reduction in the material payoffs that she would receive. This leads to an asymmetric equilibrium at which player 1 chooses a strictly lower level of extraction effort than that of player 2. Given the structure of π_r, this leads to a higher material payoff for the interdependent player than for the independent player.

3.2.2 Private Provision of Public Goods

Consider an n-person economy in which there is one public good and one private good. Each individual is endowed with an identical level of private good denoted by $b > 0$. The quantity of public good is defined as the sum of (voluntary) contributions of individuals which are paid out of their endowments.[14] Since the private good holdings of individual r would be $b - x_r$ when she contributes x_r to the production of the public good, we may write the absolute payoff of person r as a function of the profile of the contributions as follows:

$$\pi_r(x) = U(b - x_r, \sum x_q), \quad x \in [0,b]^n. \tag{11}$$

where $U : \mathbb{R}^2_+ \to \mathbb{R}_{++}$ is a twice differentiable *money-metric* utility function such that $U_1 > 0$, $U_2 > 0$, $U_{11} \leq 0$, and $U_{12} \geq 0$.[15] We also postulate the following standard boundary conditions: $U_1(0, nb) > U_2(0, nb)$ and $U_2(b, 0) > U_1(b, 0)$.

This environment induces the (symmetric) game $\Gamma^{\text{pg}} \equiv (\{[0, b], \pi_r\}_{r=1,\ldots,n})$, which we refer to as the *public good game.* It is routine to check that $\Gamma^{\text{pg}} \in \mathcal{A}$ under the assumptions stated above. Hence by Theorem 1 we may again conclude that interdependent preferences have a strategic advantage over independent preferences in the public good game.

[14] If the public good in question is something like the protection of a military front or the irrigation of a common land, this production technology might be found objectionable. For this reason, Cornes (1993), for instance, proposes to examine the model with quasiconcave CES technology, where the quantity of public good is $(\sum x_q^\alpha)^{1/\alpha}$, $\alpha \leq 1$. (Notice that this technology approaches to Hirshleifer's weakest-link technology as $\alpha \to -\infty$.) More generally, one may assume that the technology is given by any additively separable production function $x \mapsto \sum h(x_q)$ where h is any strictly increasing and concave real function on $[0, a]$. Our strategic advantage result applies to this case as well; see footnote 7.

[15] All of the assumed regularity conditions are standard (with the possible exception of $U_{12} \geq 0$ which entails that the private and public good are complements). Among the examples of commonly used functional forms for U that satisfy these postulates are $U(c, X) = V(c) + W(X)$, where V and W are twice differentiable positive functions with $V' > 0$, $V'' \leq 0$ and $W' > 0$.

4 Preference Evolution

In this section we examine the potential implications of the results obtained above for the evolutionary theory of preference formation. Along the lines of recent work by Fershtman and Weiss (1996) and Bester and Güth (1998), we consider a sequence of generations such that the distribution of preferences is fixed within a generation but varies across generations under pressure of differential material payoffs. The fundamental selection criterion that we use is a substantially weakened version of the standard notion of "payoff monotonicity," which is based on the hypothesis that higher *material* payoffs to a heritable trait lead to more rapid replication of that trait over time (see, for instance, Waldman, 1994, Bergstrom, 1995, or Robson, 1996). This hypothesis is consistent with a variety of distinct intergenerational preference transmission mechanisms. The most obvious is genetic transmission, in which children inherit the preferences of parents. In this case differential fertility rates drive the selection dynamics and payoff monotonicity corresponds to the hypothesis that number of surviving children that each parent leaves behind is an increasing function of the material payoffs that they earn in their adult life. Similarly, if preferences are acquired by emulation or inculcation within the home, and parents transmit (with or without deliberate intent) their own preferences to their children, then again differential fertility rates will drive the selection dynamics provided that parents raise their own children. If parents raise children that are not biologically their own (for instance through adoption), then high adoption rates in addition to high fertility rates will be important and payoff monotonicity implies that wealthier parents will be more likely to adopt. Preferences may also be transmitted through the emulation of non-parents, for instance through the observation of materially successful individuals in society, or may be deliberately inculcated by parents on the basis of criteria which allow for differences in the preferences of parent and child. Each of these transmission mechanisms can give rise to payoff monotonic selection dynamics under plausible assumptions.

Consider a sequence of time periods t, in each of which a population of n individuals interact strategically.[16] The material payoffs arising from the strategic interaction are represented by a symmetric n person game Γ, which is assumed to be the same in all periods. While some players maximize material payoffs, we also allow for the possibility that some have negatively interdependent preferences. The set of all available interdependent preferences is an arbitrary finite set $\mathcal{G} \subset \mathcal{F}$ with $|\mathcal{G}| = m$. The period t population composition, denoted $\mathbf{s}_t = (s_t^0, s_t^1, ..., s_t^m)$, is then an $m+1$ dimensional vector of population shares where

[16] While we assume that the population size is constant through time, this is only for convenience. The main result of this section holds so long as the population size is bounded.

s_t^0 represents the population share of players with independent preferences and s_t^j represents the population share of players with objective function Ψ_{F^j} as defined in (1) for some $F^j \in \mathcal{G}$, $j = 1, ..., m$. The number of independent players in the population in period t is simply $k_t = ns_t^0$. Finally, let $\mathbf{F}_t = (F_t^{k_t+1}, ...F_t^n) \in \mathcal{F}^{n-k_t}$ represent the $n - k_t$ dimensional vector of objective functions corresponding to each of the interdependent players, where, $F_t^i \in \mathcal{G}$, for each $i \in \{k_t + 1, ..., n\}$.

At time t, $\Gamma(\mathbf{s}_t) \equiv \Gamma_{\mathbf{F}_t}$ is played.[17] $\Gamma(\mathbf{s}_t)$ can be thought of as a random variable since we shall assume that $(\mathbf{s}_t)_{t=0}^{\infty}$ is a stochastic process. The manner in which the population composition evolves over time will depend on the payoffs obtained by each preference type at whichever equilibrium of $\Gamma(\mathbf{s}_t)$ happens to be realized in period t. Let $N(\Gamma(\mathbf{s}_t))$ represent the set of Nash equilibria of $\Gamma(\mathbf{s}_t)$, $\bar{\pi}_j(x)$ the average material payoff to individuals with objective function Ψ_{F^j}, $j = 1, ..., m$, and $\bar{\pi}_0(x)$ the average material payoff to individuals with independent preferences.

Definition. *The process $(\mathbf{s}_t)_{t=0}^{\infty}$ is said to satisfy **weak stochastic payoff monotonicity** if, for all $i = 0, ..., m$, the following conditions hold:*

(a) *If $s_t^i > 0$ and $\bar{\pi}_i(x) < \bar{\pi}_j(x)$ for all $x \in N(\Gamma(\mathbf{s}_t))$ and all $j \neq i$ with $s_t^j > 0$, then*

$$\text{Prob}\{s_{t+1}^i \leq s_t^i\} = 1 \quad \text{and} \quad \text{Prob}\{s_{t+1}^i < s_t^i\} > 0, \quad t = 0, 1, ... \tag{12}$$

(b) $\text{Prob}\{s_{t+1}^i = 0 \mid s_t^i = 0\} = 1.$

The class of all such processes is denoted by $\mathcal{S}_{\text{mon}}(\Gamma)$.

The first condition states that the population share of the preference which yields the lowest material payoff in any given generation does not grow, and that it shrinks with some positive probability. The second condition states simply that preferences that are driven to extinction under these dynamics do not subsequently recover. Other than these two restrictions, no further property is posited on the behavior of $(\mathbf{s}_t)_{t=0}^{\infty}$. In particular, this process can be time or history dependent.[18]

[17] Since $\mathbf{s}_t$ represents only the population shares of each preference type, and admits a variety of interdependent objective functions, it does not tell us the precise assignment of each objective function to each interdependent player. This is however inconsequential, since the symmetry of Γ permits any assignment of interdependent objective functions to interdependent players without affecting our results.

[18] The class of weak stochastic payoff monotonic dynamics includes as special cases both regular payoff monotonic dynamics (Samuelson and Zhang, 1992), and payoff positive dynamics (Nachbar, 1990). Also included in this class are the generalized replicator dynamics (Sethi, 1998) which are neither payoff monotonic nor payoff positive in general.

In what follows, we shall inquire whether we have

$$\lim_{t\to\infty} \text{Prob}\{s_t^0 = 0 \mid s_0^0 < 1\} = 1 \tag{13}$$

when $\Gamma \in \mathcal{A}$, and when $(\mathbf{s}_t)_{t=0}^{\infty} \in \mathcal{S}_{\text{mon}}(\Gamma)$. In other words, we ask whether weak stochastic payoff monotonic dynamics imply the elimination of independent preferences in the long run for an arbitrary initial population composition containing both independent and interdependent players. While it may at first appear that (13) follows directly from Theorem 1, the following example demonstrates that weak stochastic payoff monotonicity is actually too weak to guarantee this.

Example 1. Let $n = 2$ and suppose that $(\mathbf{s}_t)_{t=0}^{\infty}$ is a non-stationary Markov chain. Suppose that the evolution of s_t^0 is governed by the following transition matrix:

$$\Omega(t) \equiv \begin{bmatrix} 1 & 0 & 0 \\ \dfrac{1}{2^t} & 1 - \dfrac{1}{2^t} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad t = 1, 2, ...$$

(Here $\Omega_{ij}(t) = \text{Prob}\{s_{t+1}^0 = (j-1)/2 \mid s_t^0 = (i-1)/2\}$, $i, j = 1, 2, 3$.) By Theorem 1, $(\mathbf{s}_t)_{t=0}^{\infty} \in \mathcal{S}_{\text{mon}}(\Gamma)$ provided that $\Gamma \in \mathcal{A}$. However, (13) cannot hold in this case. To see this, define the events $A_0 \equiv \emptyset$ and $A_t \equiv \{s_t^0 = 0 \mid s_0^0 = 1/2\}$, and notice that $A_t \subseteq A_{t+1}$ a.s. for all $t = 1, 2, ...$. But then by continuity of probability measures, $\lim_t \text{Prob}\, A_t = \sum_{t=0}^{\infty} \text{Prob}\, A_{t+1} \backslash A_t$. But

$$\begin{aligned} \text{Prob}\, A_{t+1} \backslash A_t &= \text{Prob}\{s_{t+1}^0 = 0,\ s_t^0 = \cdots = s_1^0 = 1/2 \mid s_0^0 = 1/2\} \\ &= \text{Prob}\{s_{t+1}^0 = 0 \mid s_t^0 = 1/2\} \textstyle\prod_{j=1}^{t} \text{Prob}\{s_j^0 = 1/2 \mid s_{j-1}^0 = 1/2\} < \dfrac{1}{2^t} \end{aligned}$$

so that $\lim_t \text{Prob}\, A_t < \sum_{t=1}^{\infty} 1/2^t = 1.$[19] $\|$

Given this example, it is clear that we have to demand more from the selection dynamics. A sufficient (but not necessary) requirement is to assume that probability of the event that $s_t^0 > 0$ is strictly decreasing is bounded away from zero whenever $\bar{\pi}_0(x) < \bar{\pi}_j(x)$ for all $x \in N(\Gamma(s_t))$ and all $j \neq i$ with $s_t^j > 0$. This is not a terribly stringent requirement in that any stationary Markov chain in $\mathcal{S}_{\text{mon}}(\Gamma)$ satisfies it trivially. In the next result, we shall

[19] More generally, suppose that $n = 2$ and consider any $(\mathbf{s}_t)_{t=0}^{\infty} \in \mathcal{S}_{\text{mon}}(\Gamma)$ such that the evolution of $(s_t^0)_{t=0}^{\infty}$ is governed by a transition matrix $\Omega(t)$. Then, $\lim_t \text{Prob}\{s_t^0 = 0 \mid s_0^0 = 1/2\} = 1$ if and only if $\sum_{t=1}^{\infty} \Omega_{21}(t) = \infty$. To see the "only if" part, notice that if $\sum_{t=1}^{\infty} \Omega_{21}(t) < \infty$, then there must exist $T > 0$ such that $\sum_{t=T}^{\infty} \Omega_{21}(t) < 1$. In this case, by defining $A_t \equiv \{s_{t+T}^0 = 0 \mid s_0^0 = 1/2\}$ and applying the above argument we find $\lim_t \text{Prob}\, A_t < 1$. The "if" part is less elementary, and it follows from our subsequent Corollary 1.

prove that this requirement is sufficient to guarantee (13) for all games $\Gamma \in \mathcal{A}$. The proof of this proposition will also enable us to obtain a better (possibly time-dependent) lower bound on $\text{Prob}\{s^0_{t+1} < s^0_t \mid s^0_t \neq 0, 1\}$ as well.

Theorem 2. *Take any $k^* \in \{1, ..., n-1\}$, let $\Gamma \in \mathcal{A}$, and let $(\mathbf{s}_t)_{t=0}^{\infty} \in \mathcal{S}_{\text{mon}}(\Gamma)$. If there exists a number $\sigma > 0$ such that*

$$\text{Prob}\{s^0_{t+1} < s^0_t \mid s^0_t \neq 0, 1\} \geq \sigma, \quad t = 1, 2, ..., \tag{14}$$

then

$$\lim_{t\to\infty} \text{Prob}\{s^0_t = 0 \mid s^0_0 = k^*/n\} = 1. \tag{15}$$

Proof. Let $K \equiv n - k^*$ and consider the subprocess $(Y_t)_{t=0}^{\infty}$ where $Y_t \equiv s^0_{tK}$, $t = 0, 1, ...$. Letting $s^* \equiv k^*/n$, we have

$$\begin{aligned} \text{Prob}\{Y_1 = 0 \mid Y_0 = s^*\} &= \text{Prob}\{s^0_K = 0 \mid s^0_0 = s^*\} \\ &\geq \text{Prob}\{s^0_K < s^0_{K-1} < \cdots < s^0_1 < s^* \mid s^0_0 = s^*\} \\ &= \prod\nolimits_{t=1}^{K} \text{Prob}\{s^0_t < s^0_{t-1} \mid 0 < s^0_{t-1} < \cdots < s^0_0 = s^*\} \\ &\geq \sigma^K \end{aligned}$$

by (14). Thus,

$$\text{Prob}\{Y_1 \neq 0 \mid Y_0 = s^*\} \leq 1 - \sigma^K \tag{16}$$

and we obtain

$$\text{Prob}\{Y_1 \neq 0,\ Y_2 \neq 0 \mid Y_0 = s^*\} \leq \text{Prob}\{Y_2 \neq 0 \mid Y_1 \neq 0,\ Y_0 = s^*\}(1 - \sigma^K).$$

But since the first part of (12) implies that $\text{Prob}\{Y_2 \neq 0 \mid Y_1 = Y_0 = s^*\} \geq \text{Prob}\{Y_2 \neq 0 \mid Y_1 = i, Y_0 = s^*\}$ for all $i \geq s^*$, we must have[20]

$$\text{Prob}\{Y_2 \neq 0 \mid Y_1 \neq 0,\ Y_0 = s^*\} \leq \text{Prob}\{Y_2 \neq 0 \mid Y_1 = Y_0 = s^*\} \leq 1 - \sigma^K.$$

We thus find

$$\text{Prob}\{Y_1 \neq 0,\ Y_2 \neq 0 \mid Y_0 = s^*\} \leq (1 - \sigma^K)^2.$$

[20] Here the first inequality follows from the fact that, for any events A, B, C in any probability space with measure P, $P(A \mid B) \geq P(A \mid C)$ implies $P(A \mid B) \geq P(A \mid B \cup C)$. The second inequality is obtained in a manner analogous to (16).

Proceeding by induction, we obtain

$$\text{Prob}\{Y_t \neq 0,\ t = 1, ..., T \mid Y_0 = s^*\} \leq (1 - \sigma^K)^T, \quad T = 1, 2, ...$$

But then by letting $T \to \infty$, we find

$$\text{Prob}\{Y_t \neq 0,\ t = 1, ... \mid Y_0 = s^*\} = 0.$$

This establishes (15) in view of the continuity of probability measures. ■

Theorem 2 immediately establishes that if the selection dynamics are either deterministic or stationary Markov, then weak stochastic payoff monotonicity implies that the population share of independent agents will shrink to zero in finite time with probability one. This observation is quite general and capable of encompassing many different mechanisms for the intergenerational transmission of preferences. The following example of a parental socialization mechanism provides an illustration.

Example 2. Consider an evolutionary scenario in which the strategic interaction in any generation involves playing a game $\Gamma(\mathbf{s}_t)$, where $\mathbf{s}_t$ is the period t population composition and $\Gamma \in \mathcal{A}$. For simplicity, we assume that each adult has exactly one child, and there are only two types of admissible preferences. Hence $\mathbf{s}_t = (s_t^0, s_t^1)$, where s_t^1 is the population share of the interdependent individuals. Assume that parents attempt to socialize their children on the basis of the current equilibrium payoff distribution. Specifically, an adult wishes to inculcate preferences in her child that yield the highest value for her *own* preferences. (Bisin and Verdier, 1997, refer to this as *partial empathy.*) A parent with objective function (1), for instance, wishes to inculcate preferences in her child which yield the highest value for (1). We assume that each independent parent's socialization efforts are successful in period t with probability $\zeta_t = \zeta(s_t^0)$, where $\zeta : [0, 1] \to (0, 1)$ is a decreasing function.[21] If the parent's socialization efforts are not successful, the child simply inherits her parent's preferences.

By using Theorem 1, we may readily verify that this socialization mechanism entails a stochastic process $(\mathbf{s}_t)_{t=0}^{\infty}$ which belongs to $\mathcal{S}_{\text{mon}}(\Gamma)$. On the other hand,

$$\text{Prob}\{s_{t+1}^0 < s_t^0 \mid s_t^0 \neq 0, 1\} = 1 - \zeta(s_t^0) \geq 1 - \zeta(0) > 0$$

[21] The decreasingness of ζ captures the "oblique" aspect of cultural transmission mechanisms: the more interdependent people there are in the society, the higher is the chance of successful inculcation by the independent parents who implore their children to "do as I say, not as I do!" (Bisin and Verdier, 1997).

so that by Theorem 2, we may conclude that independent preferences are almost surely driven to extinction in finite time.[22] ‖

Finally, we note the following generalization of Theorem 2, which shows that (13) may hold under a large class of stochastic processes. The proof is a straightforward modification of that of Theorem 2, and is thus omitted.

Corollary 1. *Take any* $k^* \in \{1, ..., n-1\}$, *let* $\Gamma \in \mathcal{A}$, *and let* $(\mathbf{s}_t)_{t=0}^{\infty} \in \mathcal{S}_{\text{mon}}(\Gamma)$. *If there exists a* $\sigma(t) > 0$ *such that*

$$\text{Prob}\left\{s_{t+1}^0 < s_t^0 \mid s_t \neq 0, 1\right\} \geq \sigma(t), \quad t = 1, 2, ..., \tag{17}$$

and

$$\liminf_{T\to\infty} \prod_{j=0}^{T} \left(1 - \prod_{t=j(n-k^*)+1}^{(j+1)(n-k^*)} \sigma(t)\right) = 0$$

then (15) holds.

The next example illustrates the superiority of Corollary 1 over Theorem 2.

Example 3. Let $k^* \in \{1, ..., n-1\}$ and $K \equiv n - k^*$ and $\sigma(t) \equiv 1/t^{1/K}$, $t = 1, 2, ...$. Notice that since $\inf_{t\geq 1} \sigma(t) = 0$, we cannot use Proposition 3 to establish (15) even if (17) is satisfied. But

$$\lim_{T\to\infty} \prod_{j=0}^{T} (1 - \sigma(jK+1) \cdots \sigma((j+1)K)) \leq \prod_{t=0}^{\infty} \left(1 - \frac{1}{t}\right) = \lim_{t\to\infty} \frac{1}{t} = 0,$$

and hence by Corollary 1, we may conclude that (15) holds. ‖

The above results suggest that interdependent preferences eventually eliminate independent preferences in the long run in particular strategic environments. It is important to bear in mind, however, that our analysis has been based on the assumption that each member of the population interacts with each other member. This "playing-the-field" hypothesis is a natural starting point for the analysis of preference evolution in aggregative games, since the most common examples of such games have precisely such an interaction structure in mind. Nevertheless, this hypothesis is truly compelling only for small and relatively isolated

[22] This conclusion could not be obtained as easily if parents were to take into account the fact that their decisions might influence the population composition in the subsequent generation and therefore alter the set of equilibria. Taking this effect into account complicates the decision problem faced by parents quite substantially, however, and demands an improbably sophisticated degree of foresight even when the population size is small.

communities. In the case of larger populations, it may be more plausible to assume that individuals interact in smaller subgroups, either with their geographic or social 'neighbors,' or with individuals with whom they have been randomly matched. In random matching environments (such as those studied by Bester and Güth (1998) and Fershtman and Weiss (1996)) the link between strategic advantage and evolutionary stability is less immediate and it is entirely possible that preferences which yield a strategic advantage in each interaction may yet earn lower payoffs on average than preferences that yield a strategic disadvantage.[23] The same is true in local interaction environments of the kind explored by Eshel, Samuelson and Shaked (1998). While an exploration of preference evolution in random matching and local interaction networks is beyond the scope of this paper, it is clearly an interesting and important topic for future research.

5 Conclusions

The findings reported in this paper give some theoretical support to the hypothesis of interdependent preferences. Aggregative games of the type studied here are important from an evolutionary perspective, and the playing-the-field hypothesis is a natural starting point for the analysis of preference evolution in the context of such games.

There are several directions in which our results could be extended. It would be interesting to consider the extent to which the main result of Section 3 can be generalized to cover larger classes of games. Determining the class of all normal-form games in which interdependent preferences yield a strategic advantage over independent preferences is largely an open problem (but see Koçkesen et al., 1997b). Relaxing the restrictive assumption that all objective functions are common knowledge is a task which should also be undertaken in future work. Finally, much work remains to be done with regard to examining the implications of our strategic advantage results within the context of alternative specifications of evolution, such as models of local interaction, and alternative socialization mechanisms.

An interesting application of the present approach concerns the theory of oligopolistic

[23] In Koçkesen et al. (1997a), preference evolution under pairwise random matching is investigated for the special case of the Hawk-Dove game. The Hawk strategy becomes dominant for interdependent players if their preferences are sufficiently interdependent, causing a homogeneous population of such players to be vulnerable to invasion by a single independent player (who plays the best response, Dove). Similarly, a population of independent players is vulnerable to invasion by a (sufficiently) interdependent type since the latter's choice of Hawk elicits a best response of Dove from her opponent. As in Banerjee and Weibull (1995), and for similar reasons, a polymorphic population prevails in the long run.

competition. The payoff structure of the commons game resembles that of Cournot oligopoly, and suggests that there may be circumstances in which a profit seeking shareholder (principal) will instruct the manager (agent) of her firm to pursue objectives other than the maximization of absolute profits. This issue has already been explored for oligopolistic markets with linear demand and cost functions by Vickers (1985) and Fershtman and Judd (1987), but our findings suggest that the phenomenon will arise much more generally.

Another application concerns the investigation of anomalies frequently observed in experimental games. Our approach appears particularly well suited to explain behavior in ultimatum bargaining games, in which a concern for relative standing would predict the rejection of highly skewed offers and entail fear of retaliation on the part of the first movers (see, for instance, Bolton, 1991). Furthermore, the ultimatum bargaining environment is one in which responders with interdependent preferences will earn higher payoffs than those with independent preferences, so that evolution operating in this environment is likely to select against the latter. The examination of this issue, and others arising from the present work, are left for future research.

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